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VARIATION IN ENTRAINMENT IMPACT ESTIMATIONS BASED ON DIFFERENT MEASURES OF ACCEPTABLE UNCERTAINTY

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Renewable Energy Technologies
- Transportation

Variation in Entrainment Impact Estimation Based on Different Measures of Acceptable Uncertainty is the final report for the Environmental Effects of Cooling Water Intake Structures Project (Contract Number 500-04-025), conducted by the University of California, Santa Cruz. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/.

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Abstract

A significant number of California's coastal power plants use once-through cooling. This technology diverts huge amounts of water from a water body into the power plant's cooling system before being discharged back. Millions of small aquatic organisms that are carried along in this water flow are killed as they pass through the power plant; this impact is referred to as entrainment. Power plant operators are required to assess and, if appropriate, mitigate or compensate for entrainment impacts. To determine the size and type of projects, such as wetland restoration, that could compensate for these losses, a method known as the Area of Production Foregone is used. This method has been used in most, if not all, recent power plant entrainment studies in California. The Area of Production Foregone is an estimate of the area of habitat that, if provided, would produce the larvae lost due to entrainment and therefore compensate for the impact. This calculation is based upon another model that estimates the portion of a population lost to entrainment in comparison to the overall population in the water body affected by the cooling water intake. As the number of studies using this approach have increased, two major statistical issues remain unresolved: (1) how to estimate and incorporate statistical error into estimation of Area of Production Foregone and (2) the effect of sample size (number of species used in the assessment) on estimation of Area of Production Foregone. This study found: (1) explicit incorporation of statistical error may lead to an increase in the area of restoration or creation required for compensation; and (2) the number of species sampled dramatically affects the estimation of Area of Production Foregone, but only when the required likelihood of complete compensation is greater than 50 percent. This report documents ways to improve the use and accuracy of this method and therefore benefits California by ensuring appropriate mitigation when entrainment impacts occur.

Keywords: Once-through cooling, Area of Production Foregone, Empirical Transport Model, Habitat Production Foregone, entrainment.

Executive Summary

Introduction

Nineteen power plants in California, representing more than 19,000 megawatts of capacity and located along the state's coast, bays and estuaries, use once-through cooling technology to condense steam used in producing electricity. Once-through cooling technology requires the diversion of millions of gallons of water per day from a water body. This water is then circulated through the power plant's cooling system and then discharged back to marine water bodies.

Power plants in California using this cooling technology are subject to provisions of the U.S. Clean Water Act. Specifically, Section 316(b) of the act requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available to protect aquatic organisms from being killed or injured. Cooling water intake structures impact aquatic organisms by either impingement or entrainment. Impingement is where larger organisms are pinned against screens located at the entrance to the cooling water intake structure. Entrainment is where organisms that are small enough pass through the screens are carried by the water into the power plant's cooling systems where they are subjected to thermal, physical, or chemical stresses.

While assessment of impingement impacts can easily be determined through monitoring, the assessment of entrainment impacts presents special challenges. These include that fact that entrained organisms, which include fish and invertebrate larvae, are difficult not only to sample, but also to identify to an informative level. The distribution and variability of these populations in local waters may also be difficult to determine. Finally, there is great difficulty in scaling such losses such that the currency of impact is interpretable and useful when assessing mitigation options.

Project Objectives

The recent history of assessing the impact from entraining small marine organism by power plants has relied heavily on the use of the Empirical Transport Model. The Empirical Transport Model estimates the portion of a population that will be lost to entrainment by determining both the number of larvae from that population that will be entrained as well as the size of the larval populations found in the source water body. The source water body is the area where larvae are at risk of being entrained and is based primarily upon biological and oceanographic factors. Recent determinations using Empirical Transport models have calculated the average mortality across target species and used this number as the best estimate of mortality for all entrained organisms.

Using this information, the Area of Production Foregone (APF) can be calculated. The Area of Production Foregone, also known as Habitat Production Foregone, is an estimate of the area of habitat that, if provided, would produce enough larvae to compensate for those larvae lost due to entrainment. This has usually been based on species specific APF values that were used to generate a mean APF across species. More recently, APF estimation has incorporated the use of statistical error by developing confidence limits in APF calculation. These help provide an approach for addressing the specific question: what is the likelihood the calculated APF is large enough to provide, if used as a basis for mitigation, full compensation for the impact?

Empirical Transport Model and Area of Production estimates are based upon values derived from a limited number of target species and then used as the best estimate for all entrainable species. Target species are selected based on their abundance and the ease of collecting and identifying their larval stages. Because of this, a limited number of fish and, occasionally, crab species have been used for entrainment. The assumption, thus far untested, is that target species are reasonable representatives for the other species not targeted.

The goals of this project are to evaluate the effect of (1) incorporating statistical error in estimating Areas of Production Foregone and (2) the number of species in estimating Area of Production Foregone.

Project Outcomes

There were two major results of this study. First, as expected, explicit incorporation of statistical error leads to an increase in the area required for restoration or creation. As an example, increasing the level of confidence that the mean falls within the specified range from 50 percent to 95 percent increases the required area about 50 percent (across all studies). Using a more conservative increase from 50 to 80 percent produced, on average, an increase in area of about 25 percent. Assuming a direct relationship between area and cost, this means that the cost of increasing the likelihood of attaining full compensation from 50 to 80 percent would add an additional 25 percent to the cost of the mitigation project.
Second, the number of species sampled dramatically affects the estimate of the Area of Production Foregone, but only when the confidence limit is greater than 50 percent. The lack of change for the 50 percent confidence limit is because the expected mean does not change as a function of sample size. Instead, statistical error increases, which, when using confidence limits other than 50 percent, will affect estimates of the Area of Production Foregone. This result points to an important policy implication: if policy mandates that the 50 percent confidence limit for the Area of Production Foregone value (mean) be used to assess impacts and as a measure of compensatory mitigation, sample size is theoretically unimportant, because the expected mean does not vary with number of species assessed. The key implication of this result is that minimizing cost during sampling and assessment may be countered by the increased cost of compensatory mitigation (for example, habitat creation or restoration) due to inadequate sampling, which typically leads to greater statistical error.

Benefits to California

The California State Water Resources Control Board recently adopted a policy for assessing and mitigating the effects of power plants using once-through cooling technology. This policy identifies the use of the Habitat Production Foregone (referred to in this report as the Area of Production Foregone) as the appropriate method to show how power plant operators have achieved reductions in power plant entrainment impacts. Furthermore, other state agencies, such as the California Energy Commission and the California Coastal Commission, have used this method to identify the type and size of wetland restoration needed to address the entrainment impacts of power plants using once-through cooling. This report documents ways to improve the use and accuracy of this method and therefore benefits California by ensuring appropriate mitigation when entrainment impacts occur.

Unless otherwise noted, all tables and figures in this report were generated by the authors for this study.

1.0 Introduction

Nineteen power plants in California, representing over 19,000 MW of capacity and located along the state's coast, bays and estuaries, use once-through cooling technology to condense steam used in producing electricity. Once-through cooling technology requires the diversion through the power plant cooling system and then discharge of millions of gallons of water per day.

Power plants in California using this cooling technology are subject to provisions of the Clean Water Act. Specifically, Section 316(b) of the act requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available to protect aquatic organisms from being killed or injured by impingement (being pinned against screens at the entrance to the cooling water intake structure) or entrainment (being small enough to pass through the screens and drawn into cooling water systems and subjected to thermal, physical or chemical stresses).

While assessment of impingement impacts can easily be determined through monitoring, assessment of entrainment impacts presents special challenges. These challenges include that fact that entrained organisms, which include fish eggs and fish and invertebrate larvae, are difficult not only to sample but also to identify to an informative level. The distribution and variability of these populations in local waters are often difficult to determine. There is also great difficulty in scaling such losses such that the currency of impact is interpretable and useful when assessing mitigation options.

The recent history of assessing the impact from entraining small marine organism by the intake of cooling water by power plants has relied heavily on the use of the Empirical Transport Model (ETM). The ETM estimates the portion of a larval population that will be lost to entrainment by determining both the amount of larvae from that population that will be entrained as well as the size of the larval populations found in the source water body. The source water body is the area where larvae are at risk of being entrained and is determined by biological and oceanographic factors. Recent determinations using ET models have calculated the average mortality across target species and used this as the best estimate of mortality for all entrained organisms.

Often ET models have been used in conjunction with demographic models that translate larval losses to adults using either hindcast (Fecundity Hindcast, [FH]) or forecast modeling (Adult Equivalent Loss, [AEL]). However the utility of the FH and AEL models has been hampered by the need for species specific life history information that is lacking for many species entrained in California. These models also suffer from an attribute that is rarely talked about but is fundamentally important and which separates these models from ETM models. Results in FH and AEL models are specific to the species modeled whereas those in ETM models are applicable across species.

To understand this it is helpful to use an example. Assume that an entrainment assessment has been conducted and that all three models were used. FH modeling will estimate the number of adult females that are required to produce the entrained larvae. AEL models will estimate the number of adults that would have resulted from the lost larvae. ETM models will estimate the percent of larvae at risk that were killed due to entrainment (called proportional mortality [P_M]) and the area of the population at risk (called source water body [SWB]). Also assume that the total number of species that were used in modeling was 10. While this is a large number for most 316(b) studies, this is a tiny fraction of the species actually entrained and lost. Hence, the utility of the models must be related to the degree that the model is useful as a proxy for other species not included in the models.

This condition is essential but has never been evaluated. Both FH and AEL models will end up producing numbers of lost adults. Because of the filter of life history, particularly fecundity and early survivorship, there is no expectation that these numbers also estimate species not modeled. By contrast, ETM estimates simply yield the proportional loss of larvae and source water body. The species specific product of P_M and SWB gives the Area of Production Foregone (APF), which is an estimate of the area of habitat that if provided would produce the larvae lost due to entrainment. Importantly, APF estimates should be and have been much more robust to life history variation than either FH or AEL estimates. Hence, it is expected that some estimator of replicate measures of APF (e.g. mean, median, 95% confidence interval) may be a proxy for other species entrained but not directly modeled. Typically, mean APF has been used, but recently the 80% confidence limit was used in a case before the California Coastal Commission (Poseidon Resources [Channelside] 2008). Explicit incorporation of statistical uncertainty (that leads to confidence limits) into APF evaluation has been constrained because of the lack of assessment of the effect of such incorporation and also because the method of incorporation of uncertainty (henceforth called error) has not been vetted.

As noted, the basis of ETM for impact assessment of entrainment is target species, which are used to estimate the general effect on entrainable organisms. Such species are selected based on their abundance, their ease of collection and on the ability to determine their identity based on larval characteristics (Steinbeck et al. 2007). Because of limitation in all these criteria, the vast majority of target organisms in ETM estimation have been a select group of fish species (note, certain species of crabs are also sometimes used). Recent determinations using ET models have calculated the average proportional mortality across target species and used this as the best estimate of proportional mortality for all entrained organisms. The major, thus far untested assumption is that target species are proxies for other species not targeted. Figure 1 schematically represents target organisms as a fraction of species entrained.

The goals of this project were to evaluate the effect of (1) incorporation of statistical error in estimation of APF and (2) sample size (number of species for which APF is assessed) on estimation of APF. For the first goal, both resampling theory and traditional parametric approaches were utilized, while resampling theory was the basis of the approach to address the second goal.

Fundamentals of the Empirical Transport Model (ETM)

A detailed description of the ETM can be found in Steinbeck et al (2007). The following is derivative of that paper. Results of empirical transport modeling provide an estimate of the conditional probability of mortality (P_M) associated with entrainment. P_M requires an estimate of proportional entrainment (P_E) as an input, which is an estimate of the daily entrainment mortality on larval populations in that body of water subject to entrainment, called the source water body (SWB). Empirical transport modeling has been used extensively in recent entrainment studies in California (Steinbeck et al. 2007) and elsewhere (e.g. at the Salem Nuclear Generating Station in Delaware Bay, New Jersey and at other power stations along the east coast of the United States (Boreman et al. 1978, 1981; PSE&G 1993). ETM derivations have also been developed (MacCall et al. 1983) and used to assess impacts at the San Onofre Nuclear Generating Station (SONGS; Parker and DeMartini 1989).

The basic form of the ETM incorporated many time-, space-, and age-specific estimates of mortality as well as information regarding spawning periodicity and larval duration (Boreman et al. 1978, 1981). Much of this type of information is unknown for species entrained in California, Hence, a variation of ETM has been developed for use for coastal once through cooling (OTC) systems in California. The essence of the approach is the compounding of P_E over time, which allows estimation of P_M using assumptions about species-specific larval life histories, specifically the length of time in days that the larvae are in the water column and exposed to entrainment.

On any sampling day *i*, P_E can be expressed as follows:

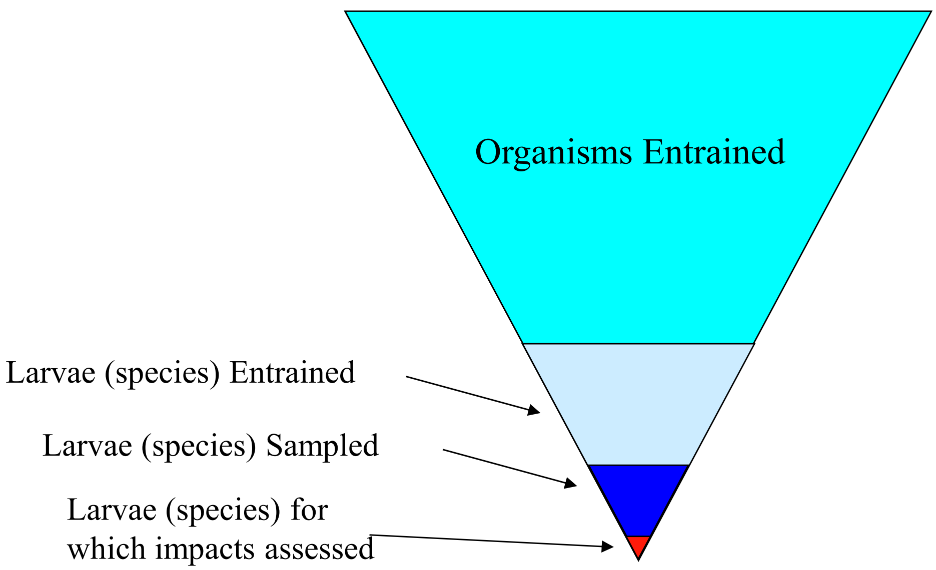

Figure 1. The inverse triangle of entrainment assessment.

$$P_{E\,i} = \frac{E_i}{N_i} \qquad (1)$$

where

E_i = total numbers of larvae of species entrained during a day during the i^{th} survey; and

N_i = numbers of larvae at risk of entrainment, i.e., abundance of larvae in the sampled source water during a day during the i^{th} survey.

Survival over one day = $1\text{-}P_{Ei}$, therefore survival over the number of days (d) that the larvae are vulnerable to entrainment = $(1\text{-}P_{Ei})^d$. Here d is determined based on a derived age distribution of entrained individuals. The derivation is based on the measured size frequency distribution of entrained individuals. Many values of d could be used, but the most common are average age and the constrained maximum (Steinbeck et al. 2007) age of entrained individuals. The difference between these two estimates can have profound effects on the estimate of impact (see below). Methods for estimating E_i and N_i can be found in Steinbeck et al. (2007).

Regardless of whether the species has a single spawning period per year or multiple overlapping spawning, the estimate of total larval entrainment mortality can be expressed as the following:

$$P_M = 1 - \sum_{i=1}^{n} f_i (1 - P_S P_{E\,i})^d \qquad (2)$$

Where:

P_{Ei} = estimate of the proportional entrainment for the i_{th} survey
P_S = ratio (sampled source water / SWB)
f_i = proportion of total annual larvae hatched during i_{th} survey
d =estimated number of days larvae vulnerable to entrainment

To establish independent survey estimates, it was assumed that each new survey represented a new, distinct cohort of larvae that was subject to entrainment. Each of the surveys was weighted using the proportion of the total population at risk during the i_{th} survey (f_i) calculated as follows:

$$f_i = \frac{N_i}{N_T} \qquad (3)$$

Where:

N_i = the source population spawned during the i^{th} survey
N_T = the sum of the N_i 's for the entire study period.

As noted above, the number of days that the larvae of a specific taxon were exposed to the mortality estimated by P_E, can be estimated using length data from a representative number of larvae from the entrainment samples. Typically, a point estimate of larval exposure has been used in the calculations (mean or maximum). These point estimates are constrained by using the values between the 1st and upper 99th percentiles of the length measurements for each entrained larval taxon. The constrained range is used to eliminate potential outlier measurements in the length data. Each measurement can then be divided by a species-specific estimate of the larval growth rate obtained from the scientific literature to produce an age frequency distribution. Maximum larval duration is calculated as the number of days between the 1st and 99th percentile. The second estimate uses an estimate of d calculated using the difference in length between the 1st percentile and the 50th percentile and is used to represent the mean number of days that the larvae were exposed to entrainment.

The term P_S represents the ratio of the area or volume of sampled source water to a larger area or volume containing the population of inference (Parker and DeMartini 1989). This allows for sampling of an area smaller than the likely source water body (SWB). If an estimate of the larval population in the larger area is available, the value of P_S can be computed directly.

There are two extreme versions of estimation of the SWB. These are noted for simplicity – the actual estimation is often more complex (Steinbeck et al. 2007). When an intake is withdrawing water exclusively from a contained water body, such as an estuary, the assumed SWB is often that water body for all species entrained. Note that even in these cases, there is often an addition to the SWB that represents tidal flux. For intakes withdrawing water from the open ocean, SWB is calculated separately for each assessed species. This calculation is based on the value of d and an estimate of net current velocity over the period of larval vulnerability. Hence P_S is then calculated as:

$$P_S = \frac{L_G}{L_P} \tag{4}$$

Where:

L_G = length of sampling area

L_P = length of alongshore current displacement based on the period (d) of larval vulnerability for a taxon

Estimation of Area of Production Foregone and Consideration of Error in its Estimation

For a more detailed treatment of this topic see Strange et al. (2004) and Steinbeck et al. (2007). One problem associated with the use of ETM approaches is in the estimation of impact and potential mitigation opportunities. This is because the currency of ETM is proportional mortality (P_M), which is not an intuitive currency for impact assessment. Calculation of the area of production foregone (APF) is one approach for estimating impact and for giving guidance to compensation strategies because it yields the amount of habitat that would need to be replaced to compensate for the larval production lost due to entrainment.

Area of Production Foregone models can be used to understand the scale of loss resulting from entrainment and the extent of mitigation that could yield compensation for the loss. The basis of APF calculations with respect to entrainment rests on the assumptions that (1) P_M information collected on a group of species having varied life history characteristics can be used to estimate to impact to all entrained species and, (2) the currency of APF (habitat acreage) is useful in understanding both direct and indirect impacts resulting from entrainment, which is essential for understanding the extent of compensation required to offset the loss.

Because APF considers taxa to be simply independent replicates useful for calculating the expected impact, the choice of taxa for analysis may differ from Habitat Replacement Cost (HRC) assessments (Steinbeck et al. 2007). For APF, the concern is that each taxon is representative of others that were either unsampled (most species including invertebrates, plants and holoplankton) or not assessed for impact (most fish species, see Figure 1). The core assumption of APF with respect to estimating impact is that the average loss across assessed taxa is the single best point estimator of the loss across all entrained organisms. This fundamental statistical-philosophic assumption of APF addresses one of the most problematic issues in impact estimation: the typical inability to estimate impact for unevaluated taxa. The calculation of APF is quite simple mathematically and in concept. Conceptually, it is an estimate of the area of habitat that would be required to replace all resources affected by the impact. Hence, for entrainment, it can be considered to be the area of habitat that would have to be added to replace lost larval resources. As an example, assume that for gobies the estimate was that 11% of larvae at risk in a 2000-acre estuary were lost to entrainment. The estimate of APF then would simply be 2,000 acres (the Source Water Body = SWB) x 11% (P_M) or 220 acres. Therefore the creation of 220 acres of new estuarine habitat would compensate for the losses of goby larvae due to entrainment. This does not mean that all biological resources were lost from an area of 220 acres, which is a common misunderstanding.

Instead it means that if 220 acres of new habitat were created then losses to gobies would be compensated for.

Mathematically then APF is the product of P_M and SWB. This calculation is done separately for each species i.

$$APF_i = P_{M_i}(SWB_i) \qquad (5)$$

Clearly the goal should not be to assess impacts to individual species. Rather it should be to estimate all direct and indirect impacts to the system and to provide guidance as to the mitigation that would be compensatory. Indeed one criticism of many assessment methodologies (e.g. Habitat Equivalency Analysis = HEA) is that there is a focus on only a limited number of taxa (Figure 1) of all that are directly affected by entrainment and that there is also no provision for estimation of indirect impacts (often food web considerations). APF, as discussed, addresses this concern by expressing impact in terms of habitat and assuming that indirect impacts are mitigated for by the complete compensation of all directly lost resources. The idea is that the addition of the right amount of habitat would lead to compensatory production of larvae and would also compensate for indirect effects resulting from the larval losses. For example, if one indirect consequence of larval losses was the loss of a food resource for seabirds, the replacement of those lost larvae should mitigate the impact to seabirds. Hence the task is to determine the right amount of habitat.

The most obvious approach, as noted, and one that is consistent with the underlying assumptions of APF is to use species specific APF values to calculate a point estimate of overall effect. The main assumptions of this approach are:

1) Species specific APF values represent random samples from a population of APF values (the family of all possible species specific APF values)
2) Each species specific APF is the mean value of a series of samples and hence has associated measurement error.

Based on these assumptions, the mean (across species) should represent the single best estimate of the impact due to entrainment.

$$\overline{APF} = \sum_{i=1}^{n} APF_i \qquad (6)$$

Because species in APF are simply independent replicates that yield a mean loss rate, habitat restored or created should not be directed by species. Instead the habitat monetized or created should represent the habitat for the populations at risk. That is, if the habitat in the SWB estuary was 60% subtidal eelgrass beds, 15% mudflats and 25% vegetated intertidal marsh, the same percentages should be maintained in the created habitat. Doing so would ensure that impacts on all affected species would be addressed. Probably the most controversial issue in APF assessment is how measurement error is accommodated, although such accommodation is part of national policy recommendations (EPA 2006). In most assessments, including Habitat Replacement Cost (HRC) (Strange et al. 2002), estimates of loss of taxa are implicitly considered to be without error. In APF, each species specific estimate is considered to be prone to (sometimes) massive error (indeed, estimates of confidence intervals in ETM calculations often cross through zero). Because of the uncertainty as to how error should be calculated and used in the calculation of estimates of compensatory mitigation, the goals of this project were to evaluate the effect of:

1) Incorporation of statistical uncertainty in estimation of APF – specifically how incorporation of error affects estimates of the likelihood that proposed mitigation acreage will be compensatory.
2) Sample size (number of species for which APF is assessed) on estimation of APF. Here the idea was to test how sensitive APF estimates are to sample size. The results of this portion of the study inform future sampling design.
3)

To address these goals, information (PM, the standard errors of PM, SWB) was collected from entrainment assessments at seven power plants (Figure 2). All assessments included empirical transport modeling and were done consistently with recent 316(b) determinations.
Sources of data are shown in Table 1 below. Note that for some power plants, data sources were corrected addendums to published studies.

Incorporation of statistical uncertainty in estimation of APF: Approach

The goal of this portion of the project was to estimate confidence limits for APF values. Such calculations would inform two questions (that mathematically are equivalent):

1) What is our confidence that the calculated APF accurately describes the impact?
2) What is the likelihood that restoration or creation of a given amount of area of habitat will lead to complete compensation for an impact?

This second question assumes that the measures used to compensate actually work. This assumption should not be left untested – instead there should always be an evaluation of the compensation measures.

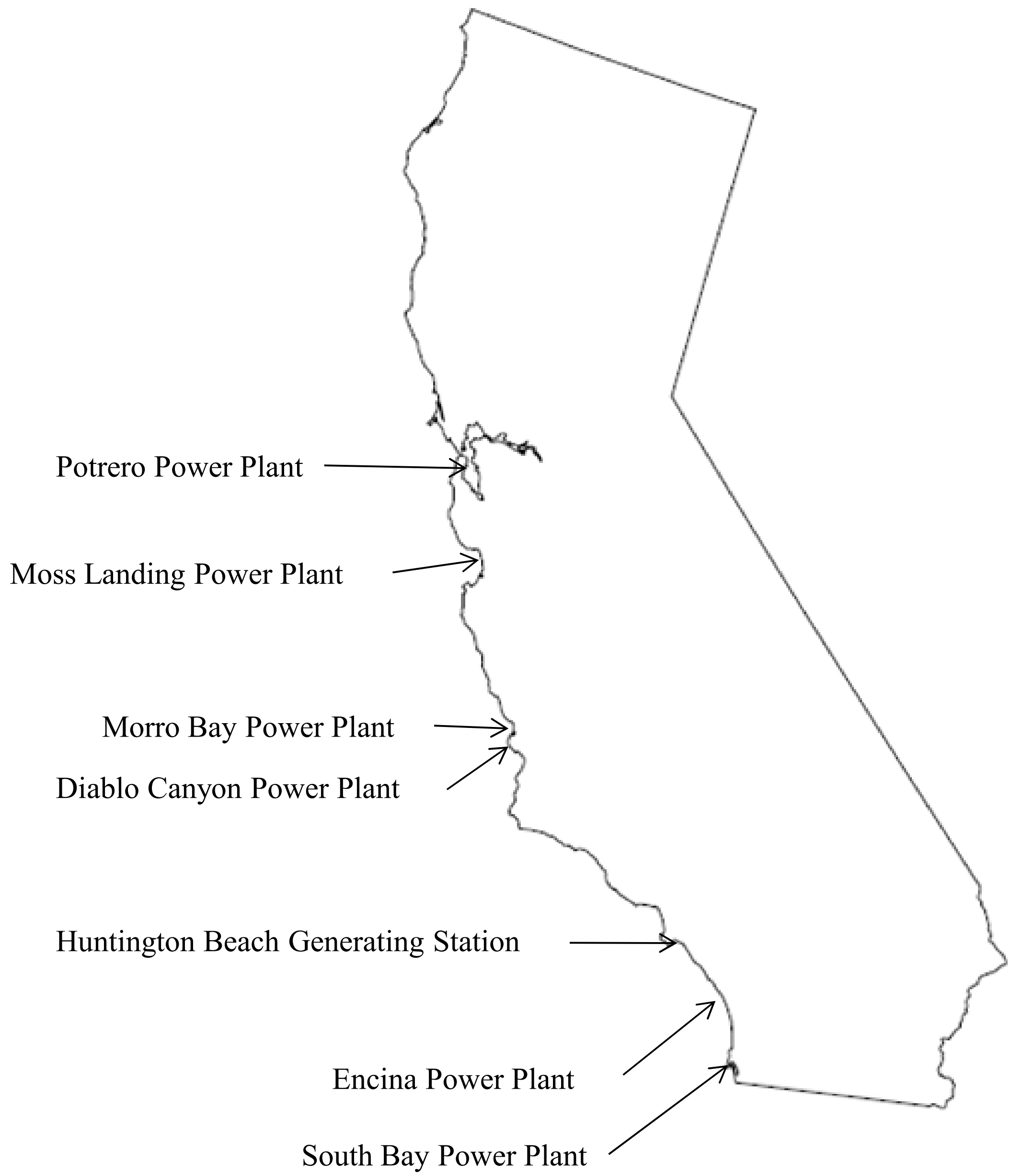

Figure 2. Location of power plants used in this study.

Power Plant	Data Source
South Bay	316(b) demonstration report to San Diego Regional Water Quality Control Board. May, 2004
Encina	316(b) demonstration report to San Diego Regional Water Quality Control Board. January 2008
Huntington Beach	AES Huntington Beach LLC Generating Station impingement and entrainment study. California Energy Commission. April 2005
Diablo Canyon	Addendum to 316(b) demonstration report. Document E9-055.0 to San Luis Obispo Regional Water Quality Control Board. March, 2000
Morro bay	Addendum to 316(b) demonstration report "Morro Bay Power Plant Modernization Project" to San Luis Obispo Regional Water Quality Control Board. July, 2001
Moss Landing	316(b) demonstration report to San Luis Obispo Regional Water Quality Control Board. April, 2000
Potrero	Final Staff Assessment: Potrero Power Plant Unit 7 Project. California Energy Commission. February 2002.

Table 1. Sources of data used in this study.

Two approaches were used to address these questions. First, based on the idea that species specific APF values are random samples from a distribution of values, confidence limits (or intervals) can be calculated using traditional parametric approaches or using resampling methods. There are substantial concerns about the use of parametric approaches (MacKinnon et al. 2004) when the underlying shape of the distribution in question is unknown or known and non-normal. APF values are synthetic not directly measured terms, and even the theoretical shape of the distribution of such values is unknown, hence both parametric and resampling methods were used and compared.

For each (treatment) combination of Power Plant, sample year, larval duration (mean or maximum period of vulnerability) and habitat (open coast or estuarine), $\overline{APF}$ (equation 6) and the standard error of APF (SE_{APF}) was calculated. These were used to generate confidence values based on a normal inverse function (Z inverse).

Generation of confidence limits for the same combinations was also calculated using resampling methods (Simon 1997). Resampling was performed with replacement and a series of 1000 means were generated for each treatment combination. Confidence limits (1, 5, 10, 20, 25, 50, 75, 80, 90, 95, 99) were determined based on the distribution of resampled means. As a reminder, the value at the 50th percentile should approximate the arithmetic mean.

Results from the two methods were compared using ordinary least squares regression for area estimated using confidence values ranging from the 50th to 99th percentiles (50, 75, 80, 90, 95, 99). The lower values (confidence values <50th percentile) were not used as they are inversely symmetric to higher values and would inflate replication.

The second approach was based on the standard errors calculated for each species P_M. See Appendix A. By assuming that the SWB was measured without error (which is probably ok for estuarine species and not ok for coastal species), confidence values for APF could be generated from the product of $P_{M(CV)}$ and

SWB, where $P_{M(CV)}$ is the P_M at a given confidence value. The underlying assumption here was that species specific APF values reflect the impact to that species and are not simply a sample from a distribution of independent measurements of the overall impact. The logic of this approach then is that the impact and confidence interval is species specific and that the net effect should reflect that logic. For example, the mean value of the 80th percentile could be calculated across species for South Bay, estuarine habitat, year one, maximum larval duration. Because parametric and resampling methodologies yielded the same results in the calculations discussed above, only the confidence limits based on the normal distribution were used. Mathematically then for any given confidence value the resulting APF would be:

$$\overline{APF_{CV}} = \sum_{i=1}^{n} APF_{CVi} \qquad (7)$$

Where:

$\overline{APF_{CV}}$ = Mean APF value across species for a given confidence value

APF_{CVi} = APF value for species i for a given confidence value

Incorporation of statistical uncertainty in estimation of APF: Results

Parametric and resampling estimation of area corresponding to similar confidence levels produced very similar results; the equation of the line comparing the two has a slope of 1 and an r^2 of .999. The results for each combination of Power Plant, sample year, larval duration (mean or maximum period of vulnerability) and habitat (open coast or estuarine) are shown in the series of Figures 1a – 1g in Appendix B. While the increase in area varied with each treatment combination, increasing likelihood of compensation resulted in an (exponential) increase in the APF estimate (Figure 3).

Using species specific confidence levels produced dramatically greater number of acres than was found using the approach using species specific APF values as replicates (Figures 2a-2g in Appendix B).

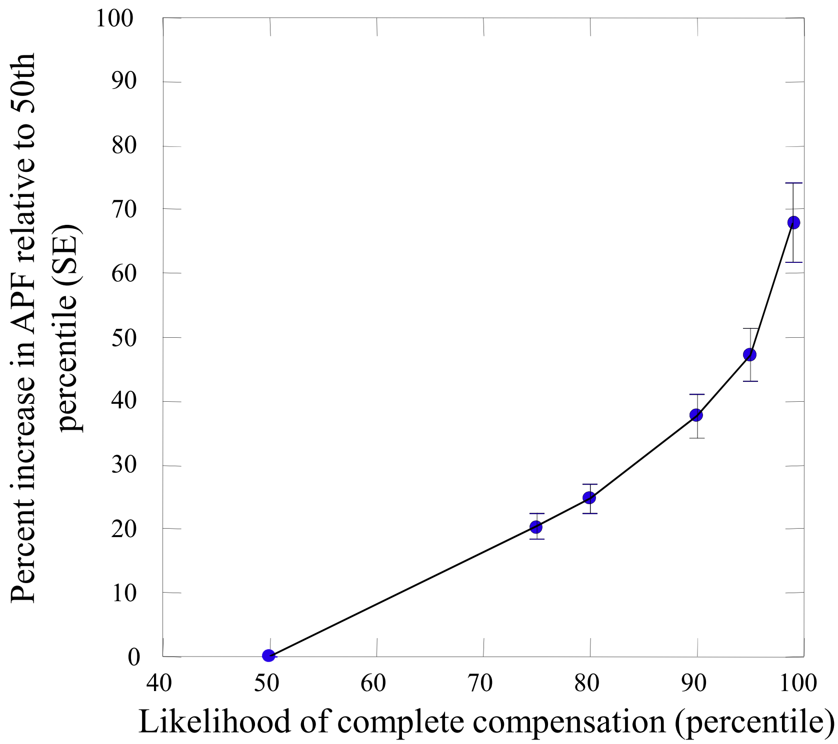

Figure 3. Effect of increasing likelihood of complete compensation on percent increase in APF.

The effect of sample size (number of species for which APF is assessed) on estimation of APF: Approach

Data from Diablo Canyon, in year one of the study, using maximum larval duration was used to assess the effect of replication on estimation of the confidence values for APF. For this treatment combination, P_M and SWB were originally calculated for 12 species and the corresponding APF values were determined as a result of this project (Appendix A). These 12 APF values were subjected to resampling in lots of 12, 11, 10, 9, 8, 7, 6, 5, 4, 3 replicates. During each run of a given level of replication, 1000 means were generated and the distribution of those means was used to determine APF values for a series of confidence values (50, 75,80, 90, 95, 99th percentile).

The effect of sample size (number of species for which APF is assessed) on estimation of APF: Results

The number of species sampled (level of replication) had a huge effect on the area required to attain a given confidence level for all levels above 50%, which is the mean (Figure 4). Using the 80% confidence level as an example, the estimated APF ranged from 3000 hectares (at 3 replicate species) to 2450 hectares (12 replicate species). Using the same line (80th percentile), one can also see that relative to the mean (50th percentile), increasing replication from 3 to 12 species decreased the area required by about 30%.

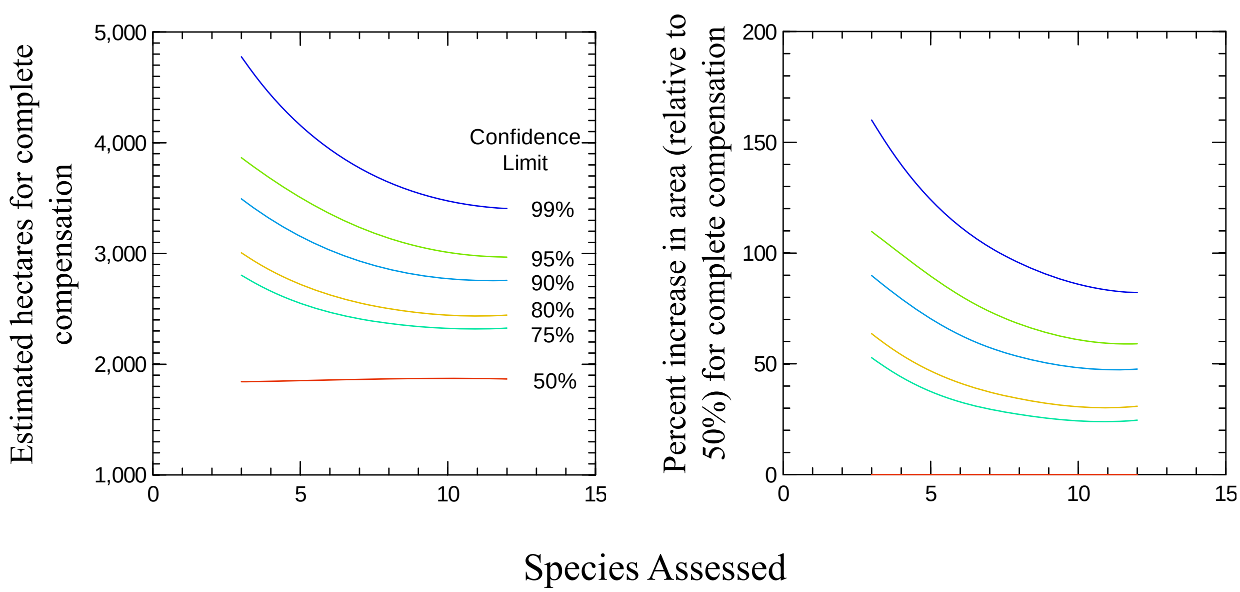

Figure 4: Effect of replication of species assessed on estimated APF.

Synthesis

Area of production foregone (APF, often also called Habitat Production Foregone; HPF) has been used in most if not all recent power plant entrainment studies in the state of California that adhered to 316(b) type assessment methods. In addition it has also been used to assess entrainment in impact studies of desalinization facilities that are co-located with power plants

(Poseidon Resources [Channelside] 2008). Far from being an unchanging approach, it has evolved considerably over the last ten years. While the derived ETM/APF approach was first used in the 316(b) assessment at Diablo Canyon (2000), the first finalized study utilizing APF was that at Moss Landing (Steinbeck et al. 2007, Moss Landing 316(b), 2000). In that assessment ETM was utilized but APF was calculated based on mean larval duration of vulnerability. In subsequent determinations at other power plants, either both mean and maximum larval durations or only maximum values were used for assessment (Appendix A). This evolution reflected the attained understanding that the true period of larval vulnerability was better estimated using maximum larval duration. Other changes in the use of APF have come in the way the SWB has been calculated for both open coast (see Diablo Canyon 316(b) and the use of an offshore gradient approach) and estuarine habitats (see Morro Bay 316(b) and the use of tidal flux). The point is that the use of APF is evolving as we understand both its constraints and the assumptions (often implicit) of the mathematics underlying its calculation.

There has also been an evolution in thinking about the most problematic general issue in impact assessment - how to account for error? In particular, an essential question is how to use confidence values to give a context to assessment of impact. In the specific case of APF, the general approach has been to use species specific APF values in the calculation of the mean APF, which is then used both as a currency of impact and also as a target value for compensatory mitigation. It is rarely if ever noted that the mean APF (from sample APF values) is (making assumption of normality) also the 50% confidence limit for the distribution of possible true population means. In non-statistical terms, this means that the true impact will be greater than or equal to the mean APF 50% of the time and equivalently that the likelihood of complete compensation from the creation of restoration of area equal to the mean APF is 50%. Two important points need to be made here. First, this argument is one about the amount of area; there is the assumption that the restoration or habitat creation actually works as designed. Second, probabilistically, half the possible population means (true impacts) are above and half below the 50th percentile (mean APF). Hence, if the true impact is above the mean APF there will be incomplete compensation, but not none at all. This last point seems obvious, but given the continued misinterpretation about APF (the wrong idea that APF means that existing habitat has been lost), it is important to be clear about the meaning of mathematical / statistical concepts.

Incorporation of confidence levels could have a profound effect on the estimation of habitat (restored or created) required to attain complete compensation for an impact. Ultimately, the confidence level desired is a policy decision that should balance the cost (financial and to society) of underestimating the area required for compensation with the cost (primarily financial) to the permittee or applicant. The results of this study provide guidance to the increase in area associated with increasing confidence that the effort will result in complete compensation. This is in turn should give insight into the trade off in costs noted above.

Conclusions

Parametric and resampling methods yield similar confidence values. Here single species APF values were considered to be independent replicate samples of the overall impact. In every combination of power plant, sample year, larval duration and habitat confidence levels (shown as likelihoods) calculated using parametric and resampling methods yielded similar results (See Appendix B). More importantly, increasing likelihoods of complete compensation were associated with increasing area of restoration or creation. The increase in area varied with treatment combination but the overall relationship revealed an exponential pattern (Figure 3). Increasing the likelihood from 50% to 95%, which is the traditional value used in inferential statistics, increased the required area about 50% (across all studies). Using a more conservative increase from 50-80% produced, on average, an increase in area of about 25%. Assuming a direct relationship between area and cost, this means that the cost of increasing the likelihood of attaining full compensation from 50 to 80% would add an additional 25% to the cost of the mitigation project.

The results of this part of the study can be used to inform other questions. As discussed, early ETM studies used the mean larval duration as the estimate of the period of larval vulnerability instead of maximum larval duration, which is currently used. The ETM study conducted at Diablo Canyon Power Plant was the most thorough investigation of entrainment impacts on the west coast and allows for a robust comparison of the effect of assumed period of larval vulnerability from mean to maximum larval duration. This change fundamentally affected estimated APF values (Figure 5). At all likelihood (of complete compensation) values greater than 50%, the area needed, under the assumption of maximum larval duration, was more than twice that needed under the assumption of mean larval duration.

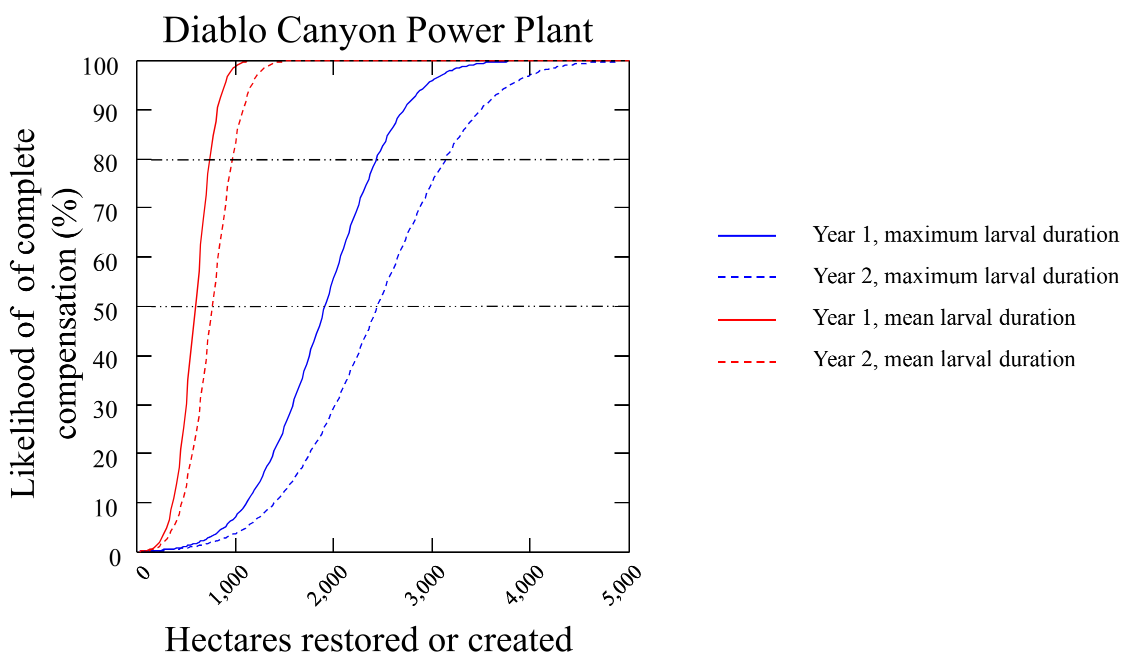

Figure 5: Probability of complete compensation as a function of area restored or created. APF estimates (using parametric approach) based from two years of sampling and two methods of estimating period of larval vulnerability

Species specific confidence values yield APF estimates much larger than those generated under the assumption that species specific APF values are replicate samples. Because standard errors were calculated for each P_M value, it was possible to calculate confidence values for each species. Using the logic discussed above and equation 7, species specific and mean confidence values were calculated. The impact of species specific estimation was large (Appendix B: Figures 2a – 2g). In all cases where the likelihood of complete compensation was greater than 50% this method yielded larger areas than that using mean confidence values; often there was a doubling of area.

The statistical-philosophical basis of this method of incorporation of measurement error is that the calculation of P_M and APF values for each species accurately describes (after error is accounted for) the impact to the species. Hence, APF values are not considered to be independent replicate samples of the overall impact of entrainment across all species be they assessed or not. Under this logic, the goal would be to ensure that the area restored or created was sufficient to compensate for the losses to each species at a given confidence level. While appealing, there are problems with this approach. First, measurement errors associated with P_M are often massive, and likely inappropriate for the task of generation of confidence values. Second, there is no provision for estimation of the impact for species not assessed (which are the vast majority of species). Third, and most fundamental, estimation of confidence values based on species specific error rates is counter to the logic of the calculation of mean APF. That is, the replication for the estimation of mean APF is the species specific APF values (not error rates), therefore the error must be based on the same replication (see Quinn and Keough 2003).

The number of species sampled dramatically affects estimation of APF (Figure 5). This clearly is not an unexpected result and is completely consistent with sampling theory (Quinn and Keough 2003, Zar 1996). Resampling the data for species sampled at Diablo Canyon, year 1, maximum larval duration showed that for all confidence levels above 50% the estimated area required to compensate for entrainment impact decreased as a function of number of species assessed. The lack of change for the 50% confidence limit is because the expected mean does not change as a function of sample size. Instead error changes, which affects the estimates of area at confidence limits different from 50%. Intuitively this is the result of the distribution of expected means broadening at low sample size. This points to an important policy implication. If policy mandates that the 50% confidence limit for the APF value (~mean) be used to assess impacts and as a measure of compensatory mitigation, sample size is theoretically unimportant, because the expected mean does not vary with number of species assessed. Note that the actual mean APF may vary across sample size. Indeed at smaller sample sizes there will be much more variability in the mean if sampled repeatedly. This would lead to a greater probability of under or over estimating the impact than would occur at higher sample size. By contrast to the situation where policy mandates use of the 50% confidence limit for APF, if policy or regulation requires incorporation of confidence values higher than 50% (e.g. Poseidon case where 80% level was used), then sample size becomes even more important. This is because the likely mitigation requirement will decrease with increasing sample size. The key implication of this result is that minimizing cost during sampling and assessment may be countered by the increased cost of habitat creation or restoration due to inadequate sampling.

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Appendix A
Data from Seven Power Plants

Table APA-1 Data from Seven Power Plants

Powerplant	Year	Habitat	Species	larval duration	Pm	Pm (SE)	offshore (km)	SWB (Hectares)	APF (Hectares)
South Bay	1	Estuarine	anchovies	maximum	0.1050	0.3132		3032.66	318.43
South Bay	1	Estuarine	CIQ goby complex	maximum	0.2150	0.4294		3032.66	652.02
South Bay	1	Estuarine	combtooth blennies	maximum	0.0310	0.1774		3032.66	94.01
South Bay	1	Estuarine	longjaw mudsucker	maximum	0.1710	0.3925		3032.66	518.59
South Bay	1	Estuarine	silversides	maximum	0.1460	0.3734		3032.66	442.77
South Bay	2	Estuarine	anchovies	maximum	0.0790	0.2814		3032.66	239.58
South Bay	2	Estuarine	CIQ goby complex	maximum	0.2670	0.4739		3032.66	809.72
South Bay	2	Estuarine	combtooth blennies	maximum	0.0340	0.1849		3032.66	103.11
South Bay	2	Estuarine	longjaw mudsucker	maximum	0.5020	0.5368		3032.66	1522.40
South Bay	2	Estuarine	silversides	maximum	0.1490	0.4121		3032.66	451.87
Encina	1	Coastal	California halibut	maximum	0.0015	0.0024	3	11117.30	16.79
Encina	1	Coastal	northern anchovy	maximum	0.0017	0.0026	3	6299.80	10.39
Encina	1	Coastal	queenfish	maximum	0.0037	0.0049	3	8217.14	29.99
Encina	1	Coastal	spotfin croaker	maximum	0.0063	0.0153	3	5558.65	35.24
Encina	1	Coastal	white croaker	maximum	0.0014	0.0028	3	13499.58	18.63
Encina	1	Estuarine	blennies	maximum	0.0864	0.1347		123.00	10.55
Encina	1	Estuarine	Garibaldi	maximum	0.0648	0.1397		123.00	7.92
Encina	1	Estuarine	gobies	maximum	0.2160	0.3084		123.00	26.39
Huntington Beach	1	Coastal	black croaker	maximum	0.0010	0.0007	4.44	8620.58	8.62
Huntington Beach	1	Coastal	blennies	maximum	0.0080	0.0054	4.44	5687.81	45.50
Huntington Beach	1	Coastal	California halibut	maximum	0.0030	0.0020	4.44	13730.72	41.19
Huntington Beach	1	Coastal	diamond turbot	maximum	0.0060	0.0040	4.44	7509.68	45.06
Huntington Beach	1	Coastal	northern anchovy	maximum	0.0120	0.0080	4.44	31993.92	383.93
Huntington Beach	1	Coastal	queenfish	maximum	0.0060	0.0040	4.44	37726.16	226.36
Huntington Beach	1	Coastal	rock crab megalops	maximum	0.0110	0.0074	4.44	11775.54	129.53
Huntington Beach	1	Coastal	spotfin croaker	maximum	0.0030	0.0020	4.44	7509.68	22.53
Huntington Beach	1	Coastal	white croaker	maximum	0.0070	0.0047	4.44	21240.41	148.68
Diablo Canyon	1	Coastal	blackeye goby	maximum	0.1151	0.0832	3	8560.80	985.69
Diablo Canyon	1	Coastal	blue rockfish complex	maximum	0.0041	0.0479	3	14146.20	58.14
Diablo Canyon	1	Coastal	cabezon	maximum	0.0111	0.1371	3	12058.20	134.21
Diablo Canyon	1	Coastal	California halibut	maximum	0.0047	0.0901	3	21088.80	98.27
Diablo Canyon	1	Coastal	clinid kelpfishes	maximum	0.1894	0.1218	3	29962.80	5674.65
Diablo Canyon	1	Coastal	KGB rockfishes	maximum	0.0388	0.0495	3	20149.20	781.59
Diablo Canyon	1	Coastal	monkeyface prickleback	maximum	0.1377	0.0726	3	31894.20	4390.56
Diablo Canyon	1	Coastal	painted greenling	maximum	0.0629	0.0920	3	26465.40	1664.67
Diablo Canyon	1	Coastal	sanddabs	maximum	0.0103	0.0583	3	12371.40	127.67
Diablo Canyon	1	Coastal	smoothhead sculpin	maximum	0.1139	0.0843	3	36122.40	4115.06
Diablo Canyon	1	Coastal	snubnose sculpin	maximum	0.1494	0.0967	3	31737.60	4741.91
Diablo Canyon	1	Coastal	white croaker	maximum	0.0070	0.0368	3	23437.80	163.60
Diablo Canyon	1	Coastal	blackeye goby	mean	0.0885	0.0774	3	4802.40	425.16
Diablo Canyon	1	Coastal	blue rockfish complex	mean	0.0028	0.0479	3	9657.00	26.75
Diablo Canyon	1	Coastal	cabezon	mean	0.0068	0.1373	3	10179.00	69.12
Diablo Canyon	1	Coastal	California halibut	mean	0.0029	0.0902	3	9291.60	26.95
Diablo Canyon	1	Coastal	clinid kelpfishes	mean	0.1498	0.1248	3	11745.00	1759.40
Diablo Canyon	1	Coastal	KGB rockfishes	mean	0.0242	0.0442	3	12423.60	300.53
Diablo Canyon	1	Coastal	monkeyface prickleback	mean	0.1056	0.0710	3	12319.20	1300.29
Diablo Canyon	1	Coastal	painted greenling	mean	0.0478	0.0920	3	14616.00	698.64
Diablo Canyon	1	Coastal	sanddabs	mean	0.0088	0.0581	3	9239.40	81.49
Diablo Canyon	1	Coastal	smoothhead sculpin	mean	0.0862	0.0767	3	12580.20	1084.16
Diablo Canyon	1	Coastal	snubnose sculpin	mean	0.1045	0.0961	3	12423.60	1297.89
Diablo Canyon	1	Coastal	white croaker	mean	0.0047	0.0368	3	11170.80	52.84
Diablo Canyon	2	Coastal	blackeye goby	maximum	0.0652	0.0576	3	6577.20	429.03
Diablo Canyon	2	Coastal	blue rockfish complex	maximum	0.0277	0.0372	3	15816.60	437.80
Diablo Canyon	2	Coastal	cabezon	maximum	0.0152	0.0651	3	9970.20	151.25
Diablo Canyon	2	Coastal	California halibut	maximum	0.0712	0.0793	3	16547.40	1177.84
Diablo Canyon	2	Coastal	clinid kelpfishes	maximum	0.2497	0.1132	3	22863.60	5709.96
Diablo Canyon	2	Coastal	KGB rockfishes	maximum	0.0480	0.0793	3	22863.60	1098.37
Diablo Canyon	2	Coastal	monkeyface prickleback	maximum	0.1176	0.0894	3	31737.60	3731.39
Diablo Canyon	2	Coastal	painted greenling	maximum	0.0558	0.0666	3	23176.80	1293.96
Diablo Canyon	2	Coastal	sanddabs	maximum	0.0080	0.0749	3	14302.80	113.99
Diablo Canyon	2	Coastal	smoothhead sculpin	maximum	0.2257	0.1133	3	26569.80	5997.34
Diablo Canyon	2	Coastal	snubnose sculpin	maximum	0.3102	0.1383	3	27405.00	8500.48
Diablo Canyon	2	Coastal	white croaker	maximum	0.0347	0.0349	3	20358.00	707.03
Diablo Canyon	2	Coastal	blackeye goby	mean	0.0412	0.0445	3	4489.20	185.00
Diablo Canyon	2	Coastal	blue rockfish complex	mean	0.0293	0.0400	3	6942.60	203.21
Diablo Canyon	2	Coastal	cabezon	mean	0.0117	0.0650	3	6525.00	76.15
Diablo Canyon	2	Coastal	California halibut	mean	0.0606	0.0847	3	5637.60	341.69
Diablo Canyon	2	Coastal	clinid kelpfishes	mean	0.1797	0.1314	3	10022.40	1800.72
Diablo Canyon	2	Coastal	KGB rockfishes	mean	0.0472	0.0798	3	8769.60	413.49
Diablo Canyon	2	Coastal	monkeyface prickleback	mean	0.1153	0.1025	3	9135.00	1053.08
Diablo Canyon	2	Coastal	painted greenling	mean	0.0369	0.0632	3	14824.80	546.89
Diablo Canyon	2	Coastal	sanddabs	mean	0.0101	0.0751	3	7151.40	72.01
Diablo Canyon	2	Coastal	smoothhead sculpin	mean	0.1562	0.1303	3	10544.40	1647.14
Diablo Canyon	2	Coastal	snubnose sculpin	mean	0.1851	0.1091	3	14302.80	2647.59
Diablo Canyon	2	Coastal	white croaker	mean	0.0280	0.0364	3	8091.00	226.87

Data from Seven Power Plants (cont.)

Powerplant	Year	Habitat	Species	larval duration	Pm	Pm (SE)	offshore (km)	SWB (Hectares)	APF (Hectares)
Morro Bay	1	Coastal	cabezon	mean	0.0249	0.5373	3	17151.30	427.07
Morro Bay	1	Coastal	KGB rockfishes	mean	0.0271	0.5733	3	15988.50	433.29
Morro Bay	1	Coastal	northern lampfish	mean	0.0253	0.8518	3	20930.40	529.54
Morro Bay	1	Coastal	Pacific staghorn sculpin	mean	0.0513	1.1220	3	45058.50	2311.50
Morro Bay	1	Coastal	white croaker	mean	0.0434	1.0526	3	20058.30	870.53
Morro Bay	1	Estuarine	combtooth blennies	maximum	0.7371	0.6012	3	930.58	685.93
Morro Bay	1	Estuarine	gobies	maximum	0.4333	0.5551	3	930.58	403.22
Morro Bay	1	Estuarine	jacksmelt	maximum	0.4392	0.5451	3	930.58	408.71
Morro Bay	1	Estuarine	Pacific herring	maximum	0.2544	0.4510	3	930.58	236.74
Morro Bay	1	Estuarine	shadow goby	maximum	0.0643	0.2625	3	930.58	59.84
Morro Bay	1	Estuarine	combtooth blennies	mean	0.4972	0.6114	3	930.58	462.68
Morro Bay	1	Estuarine	gobies	mean	0.1158	0.3357	3	930.58	107.76
Morro Bay	1	Estuarine	jacksmelt	mean	0.2172	0.4348	3	930.58	202.12
Morro Bay	1	Estuarine	Pacific herring	mean	0.1642	0.3927	3	930.58	152.80
Morro Bay	1	Estuarine	shadow goby	mean	0.0283	0.1923	3	930.58	26.34
Moss Landing	1	Estuarine	bay goby	mean	0.2144	0.0406		1213.80	260.26
Moss Landing	1	Estuarine	blackeye goby	mean	0.0749	0.0476		1213.80	90.89
Moss Landing	1	Estuarine	combtooth blennies	mean	0.1820	0.0786		1213.80	220.85
Moss Landing	1	Estuarine	gobies	mean	0.1069	0.0067		1213.80	129.76
Moss Landing	1	Estuarine	longjaw mudsucker	mean	0.0894	0.0216		1213.80	108.56
Moss Landing	1	Estuarine	Pacific herring	mean	0.1337	0.0168		1213.80	162.30
Moss Landing	1	Estuarine	Pacific staghorn sculpin	mean	0.1179	0.0198		1213.80	143.09
Moss Landing	1	Estuarine	white croaker	mean	0.1291	0.0242		1213.80	156.73
Potrero	1	Estuarine	bay goby	maximum	0.0025	0.0013		39670.22	99.57
Potrero	1	Estuarine	California halibut	maximum	0.0076	0.0066		39670.22	303.08
Potrero	1	Estuarine	gobies	maximum	0.0048	0.0017		39670.22	191.61
Potrero	1	Estuarine	northern anchovy	maximum	0.0029	0.0020		39670.22	115.44
Potrero	1	Estuarine	Pacific herring	maximum	0.0035	0.0104		39670.22	139.64
Potrero	1	Estuarine	white croaker	maximum	0.0049	0.0037		39670.22	195.57
Potrero	1	Estuarine	yellowfin goby	maximum	0.0017	0.0009		39670.22	67.44
Potrero	1	Estuarine	bay goby	mean	0.0011	0.0005		39670.22	44.43
Potrero	1	Estuarine	California halibut	mean	0.0024	0.0021		39670.22	95.21
Potrero	1	Estuarine	gobies	mean	0.0011	0.0004		39670.22	41.65
Potrero	1	Estuarine	northern anchovy	mean	0.0005	0.0004		39670.22	21.03
Potrero	1	Estuarine	Pacific herring	mean	0.0011	0.0032		39670.22	42.45
Potrero	1	Estuarine	white croaker	mean	0.0011	0.0008		39670.22	44.03
Potrero	1	Estuarine	yellowfin goby	mean	0.0009	0.0005		39670.22	36.50

APPENDIX B
Power Plant Specific Figures

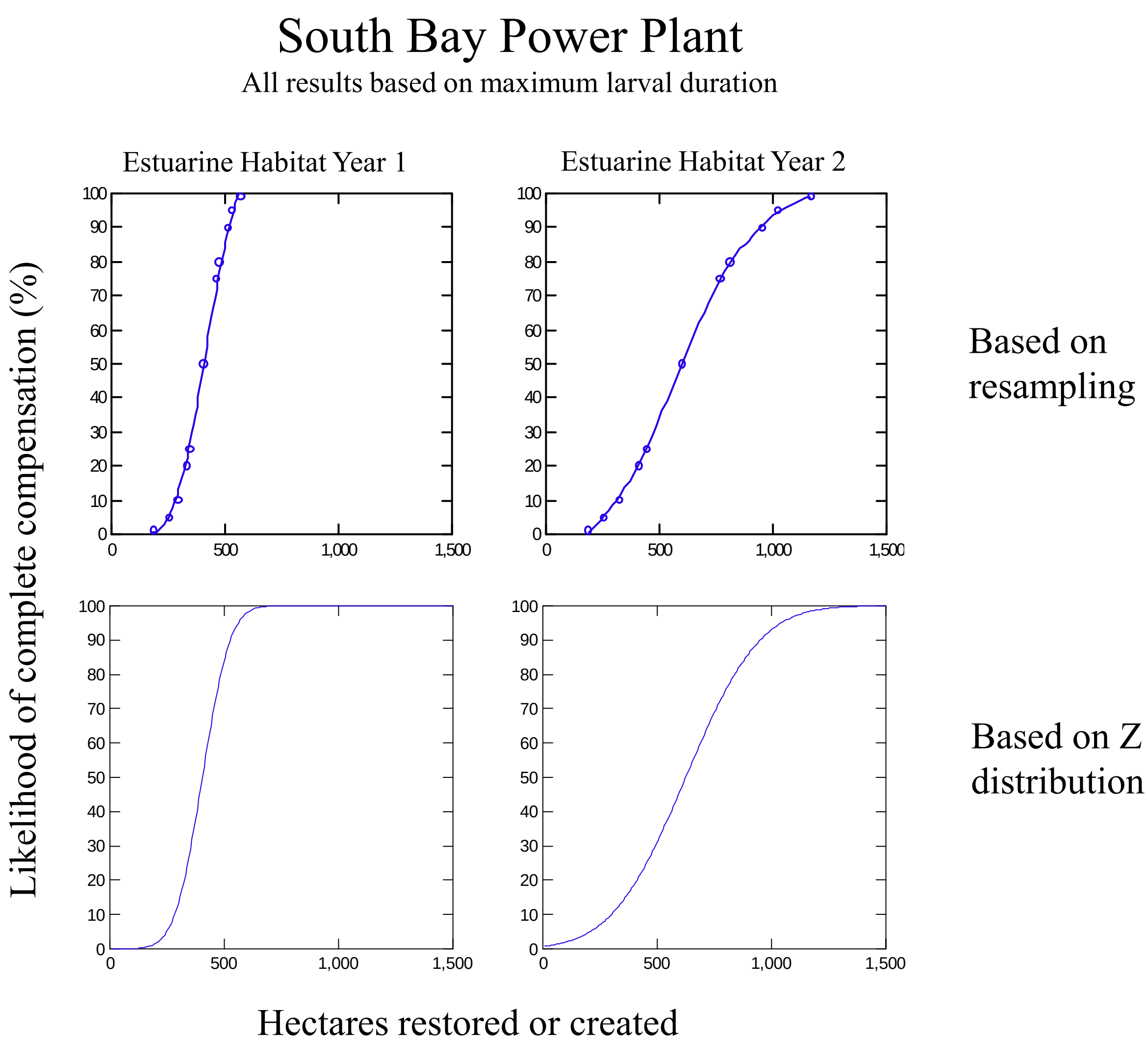

Figure 1a. Hectares restored or created at South Bay Power Plant.

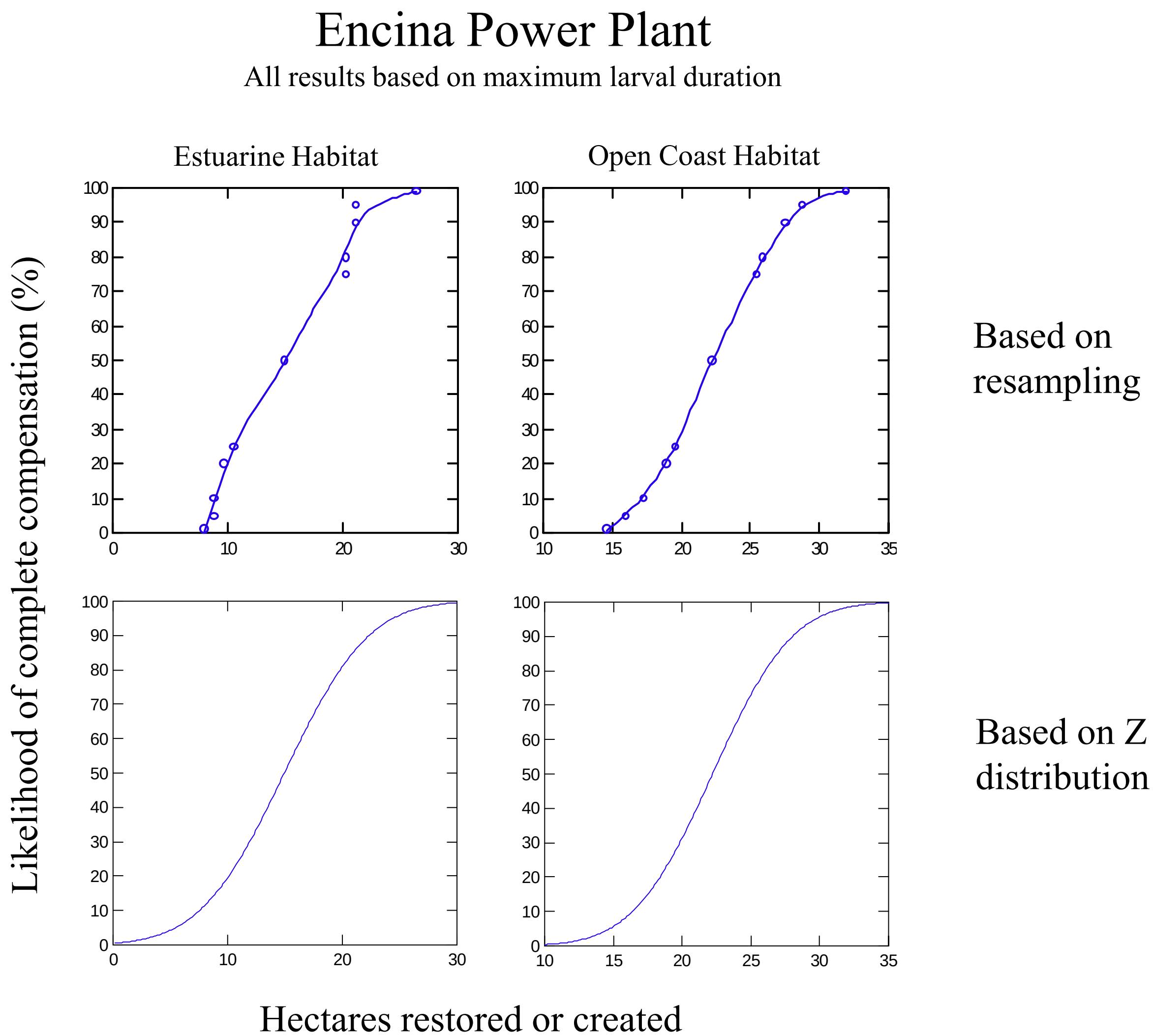

Figure 1b. Hectares restored or created at Encina Power Plan**t.**

Huntington Beach Generating Station

All results based on maximum larval duration

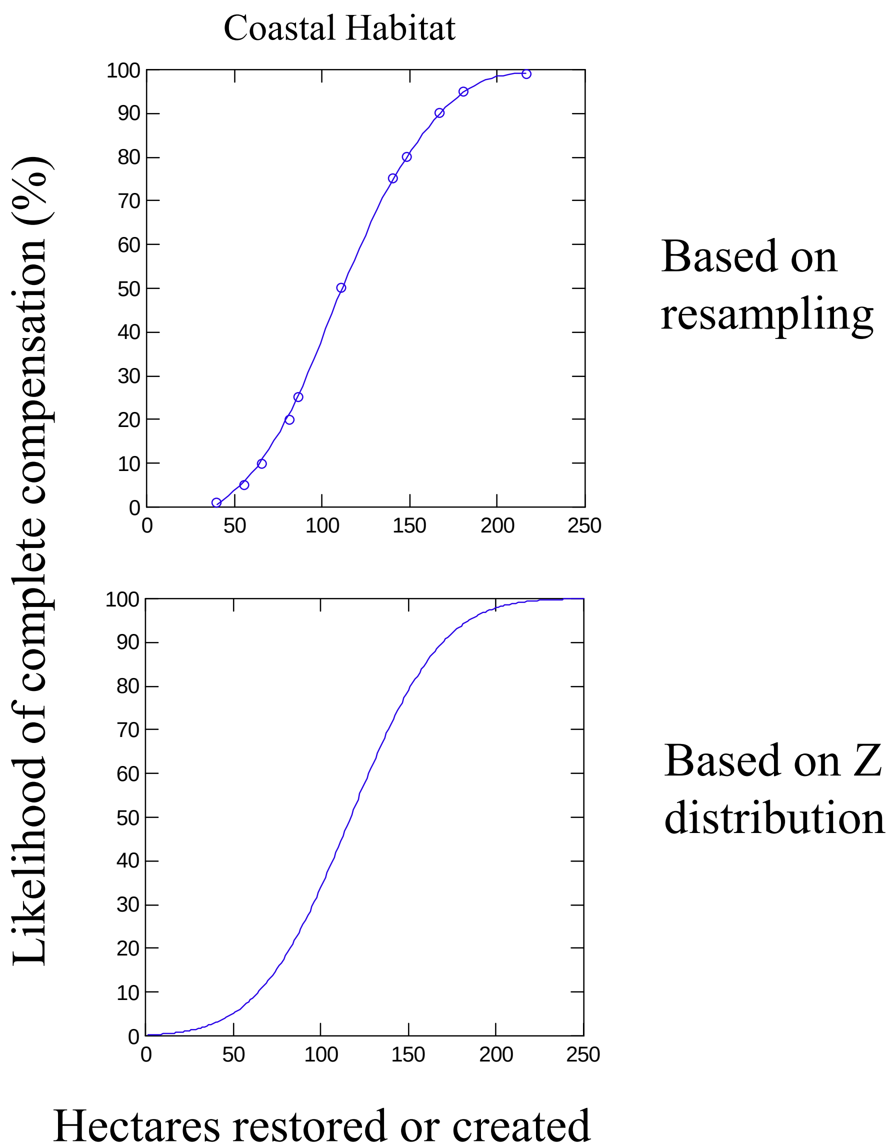

Figure 1c. Hectares restored or created at Huntington Beach Generating Station.

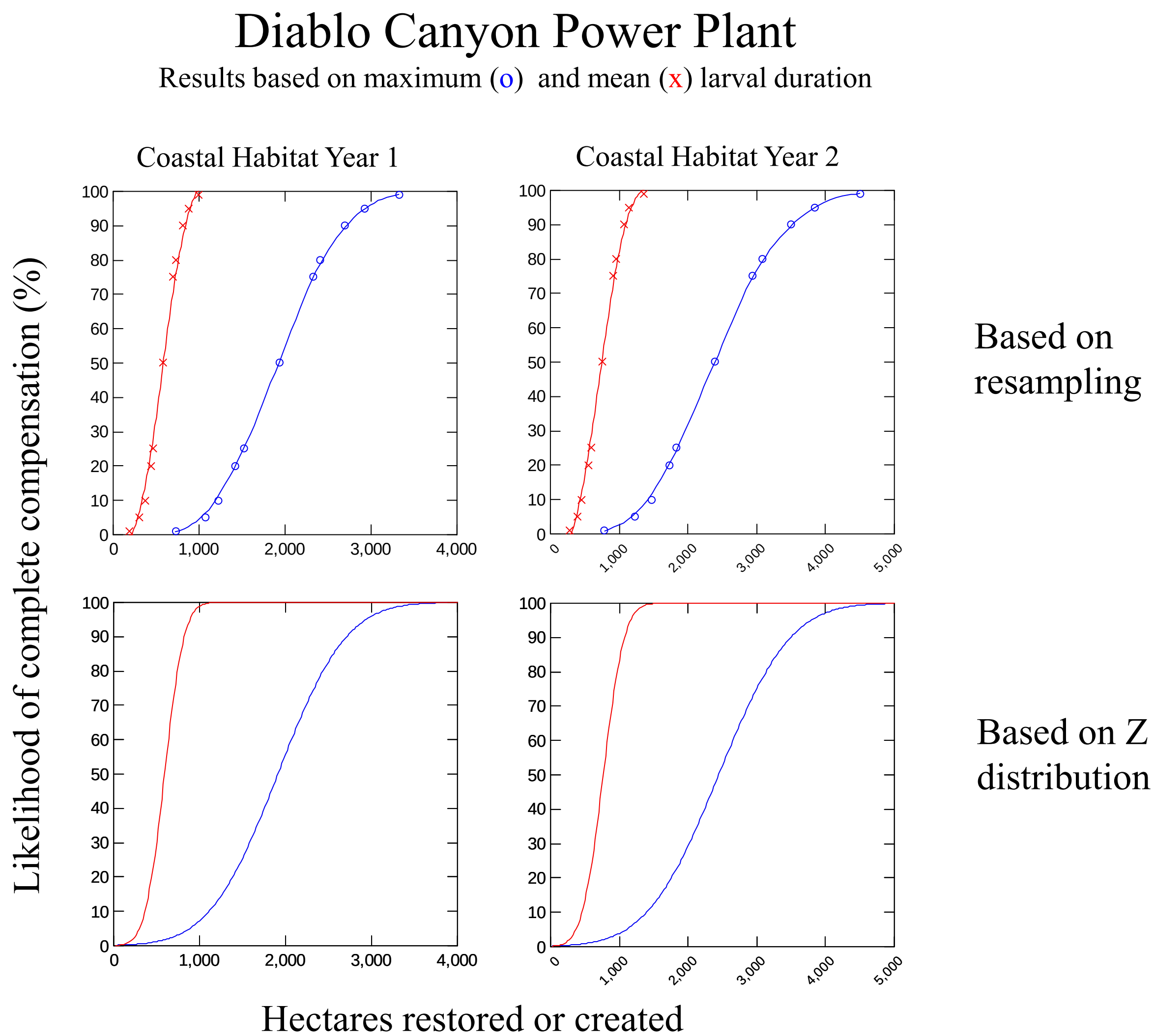

Figure 1d. Hectares restored or created at Diablo Canyon Power Plant.

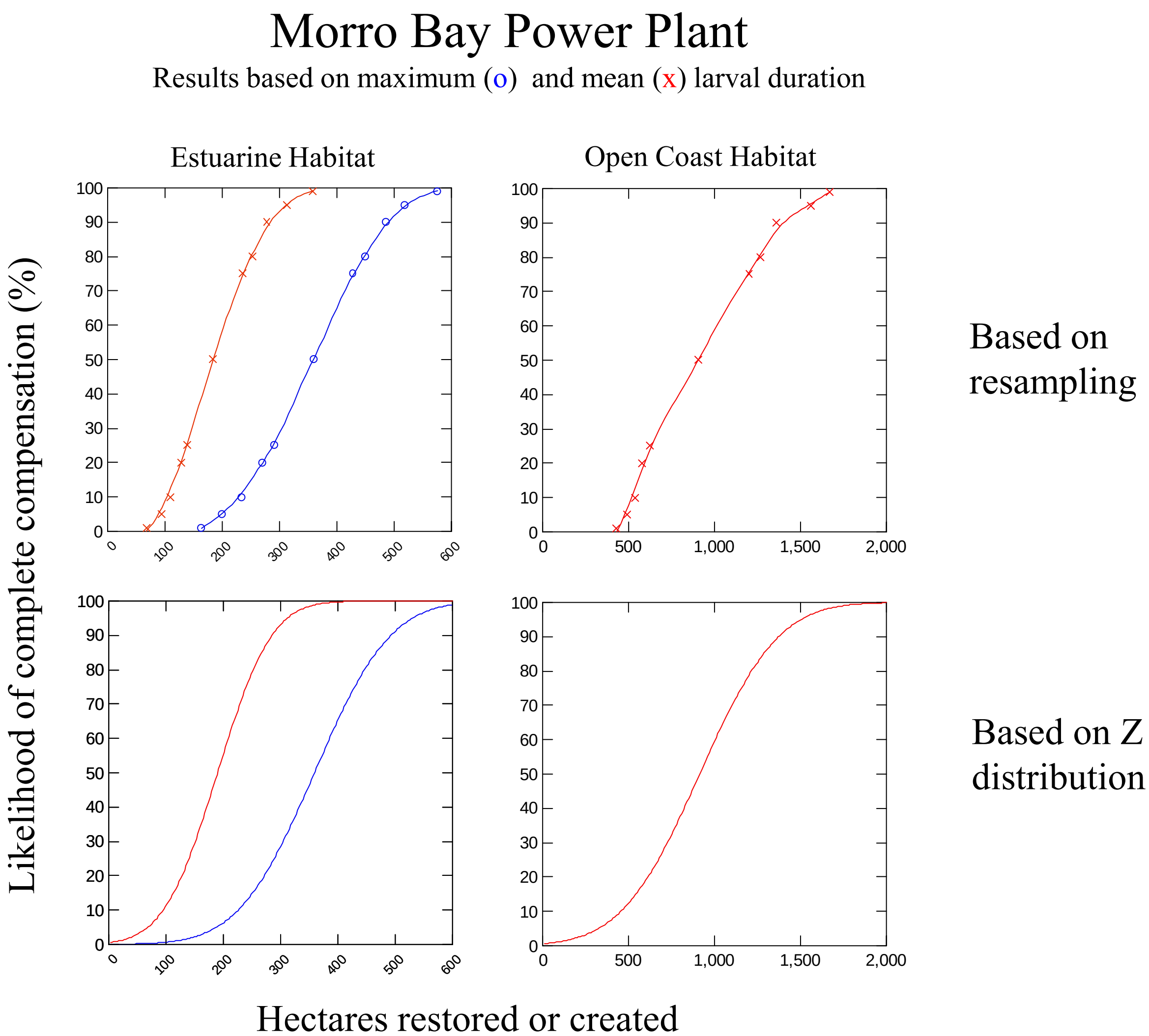

Figure 1e. Hectares restored or created at Morro Bay Power Plant.

Moss Landing Power Plant

All results based on *mean* larval duration

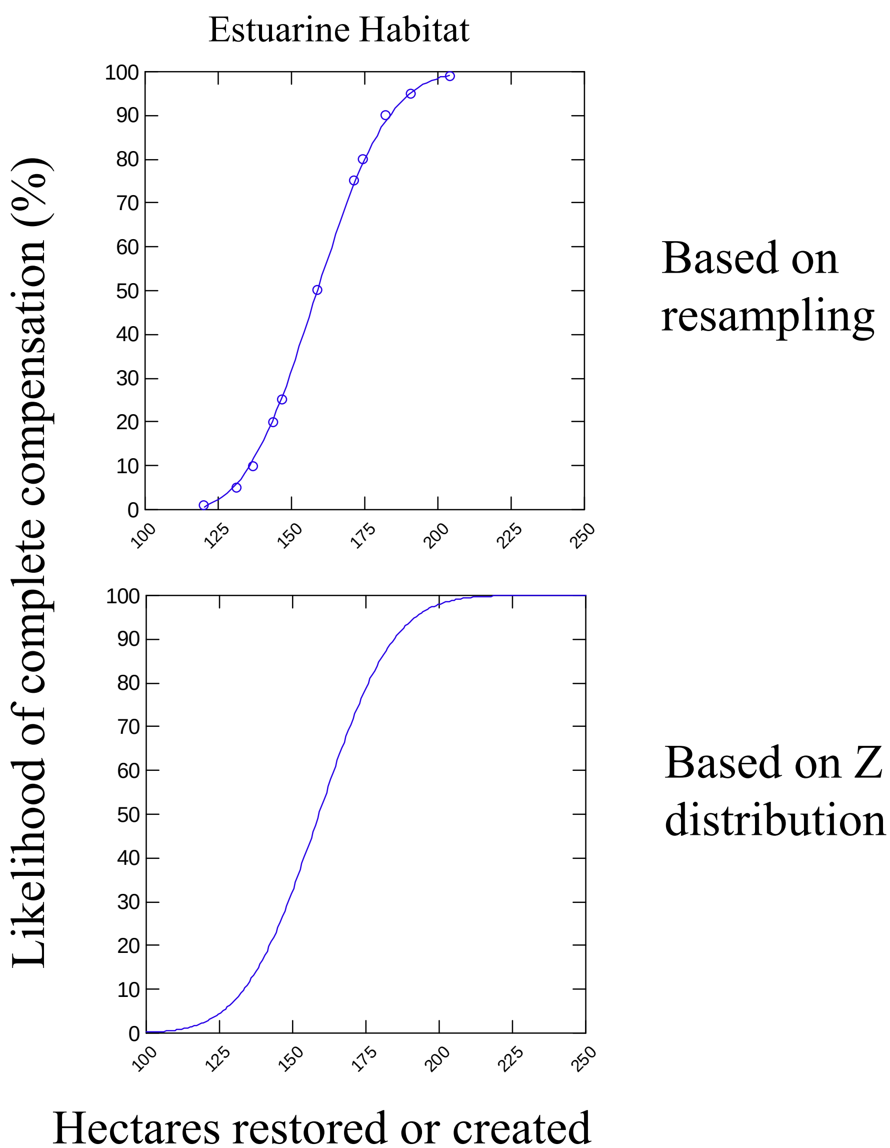

Figure 1f. Hectares restored or created at Moss Landing Power Plant.

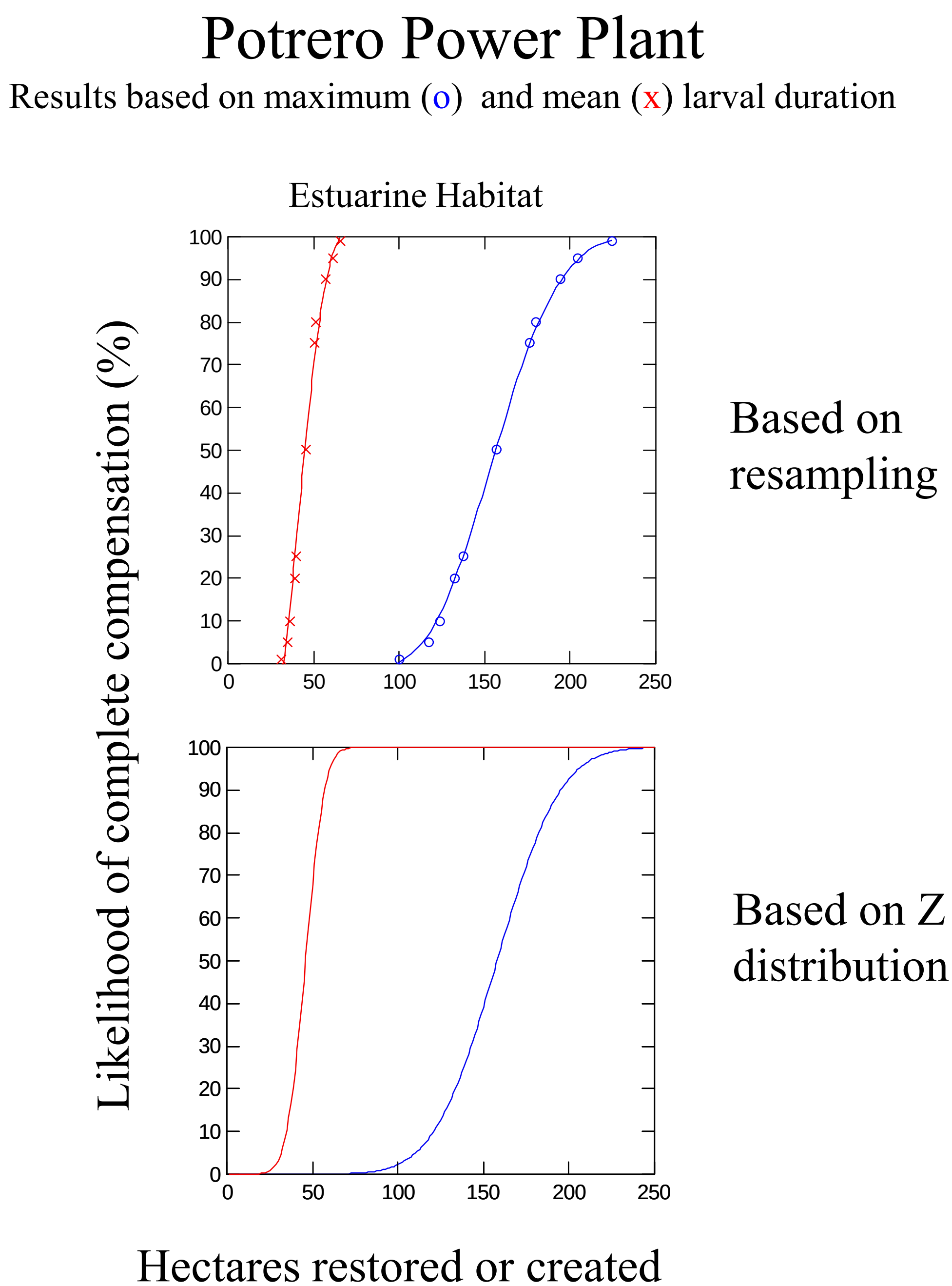

Figure 1g. Hectares restored or created Potrero Power Plant

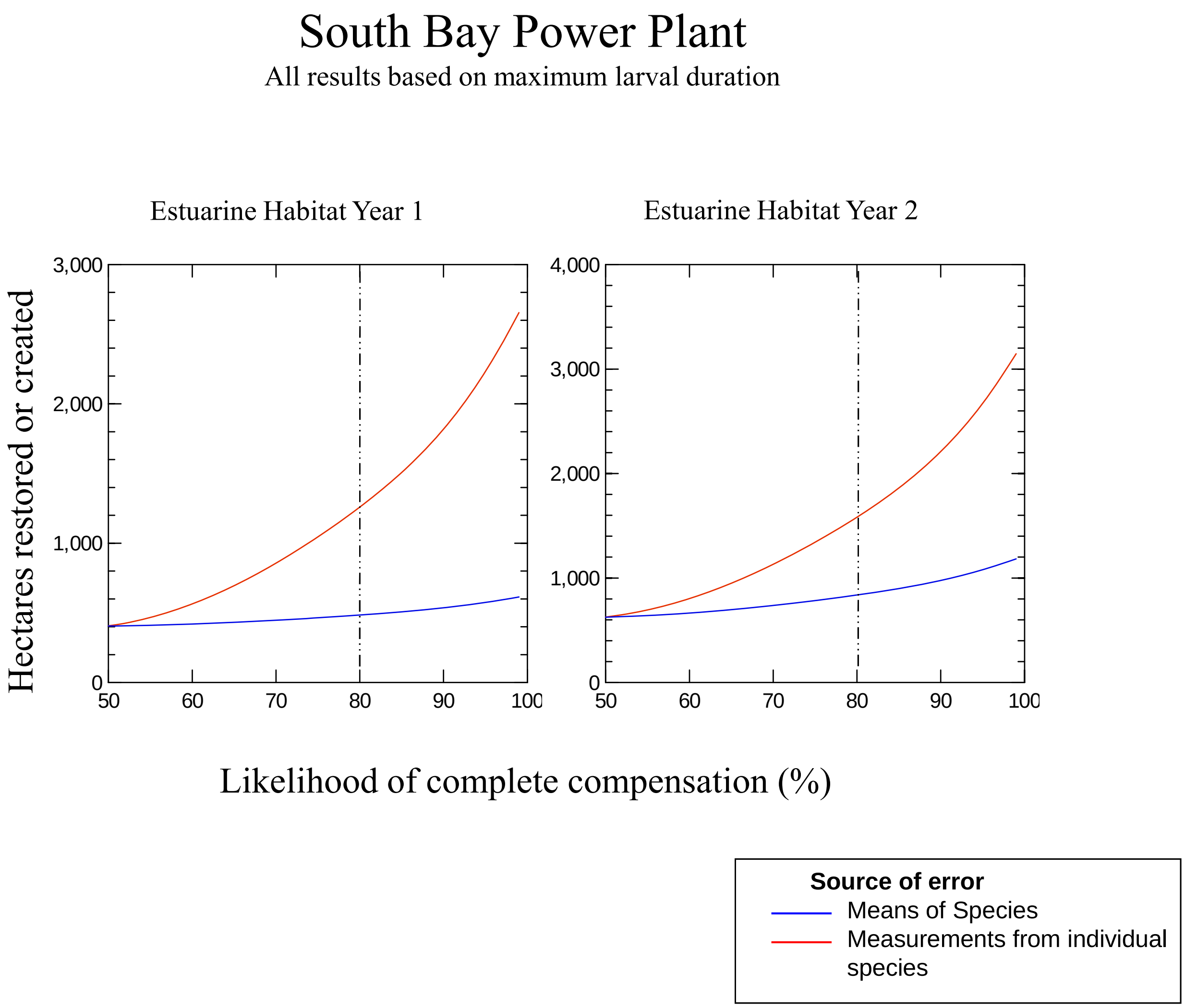

Figure 2a. Likelihood of complete compensation (%) South Bay Power Plant.

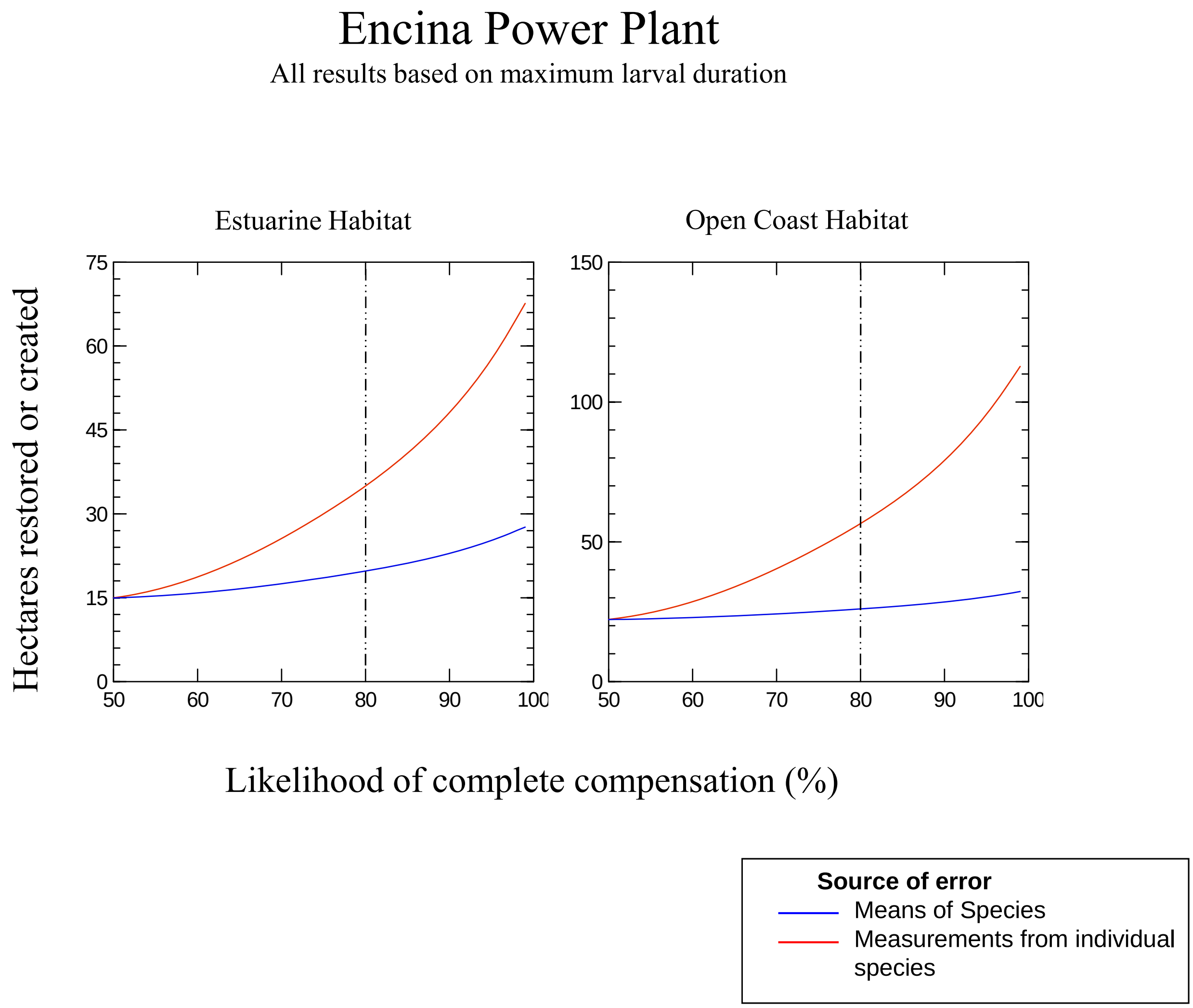

Figure 2b. Likelihood of complete compensation (%) Encina Power Plant.

Huntington Beach Generating Station

All results based on maximum larval duration

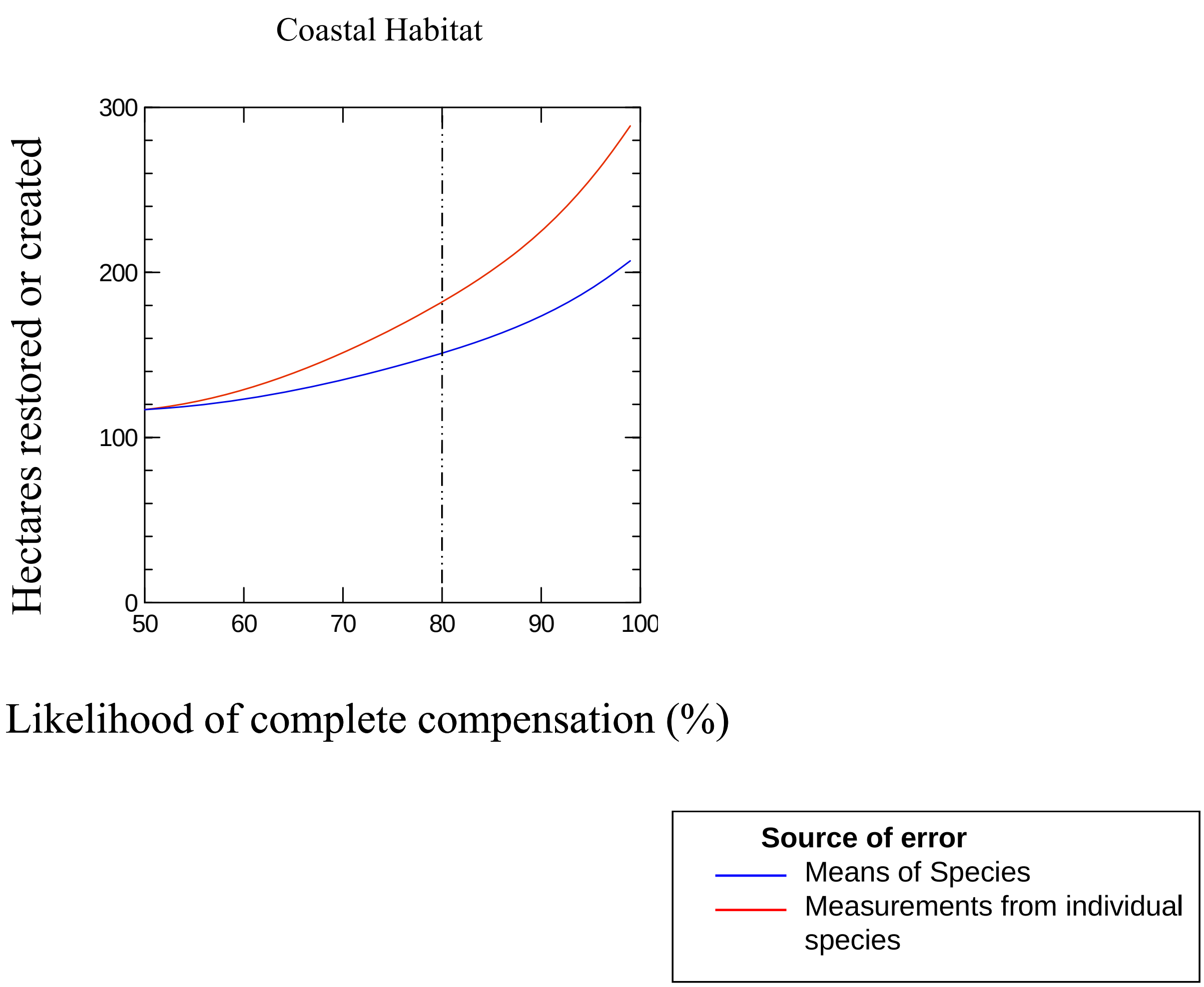

Figure 2c. Likelihood of complete compensation (%) Huntington Beach Generating Station.

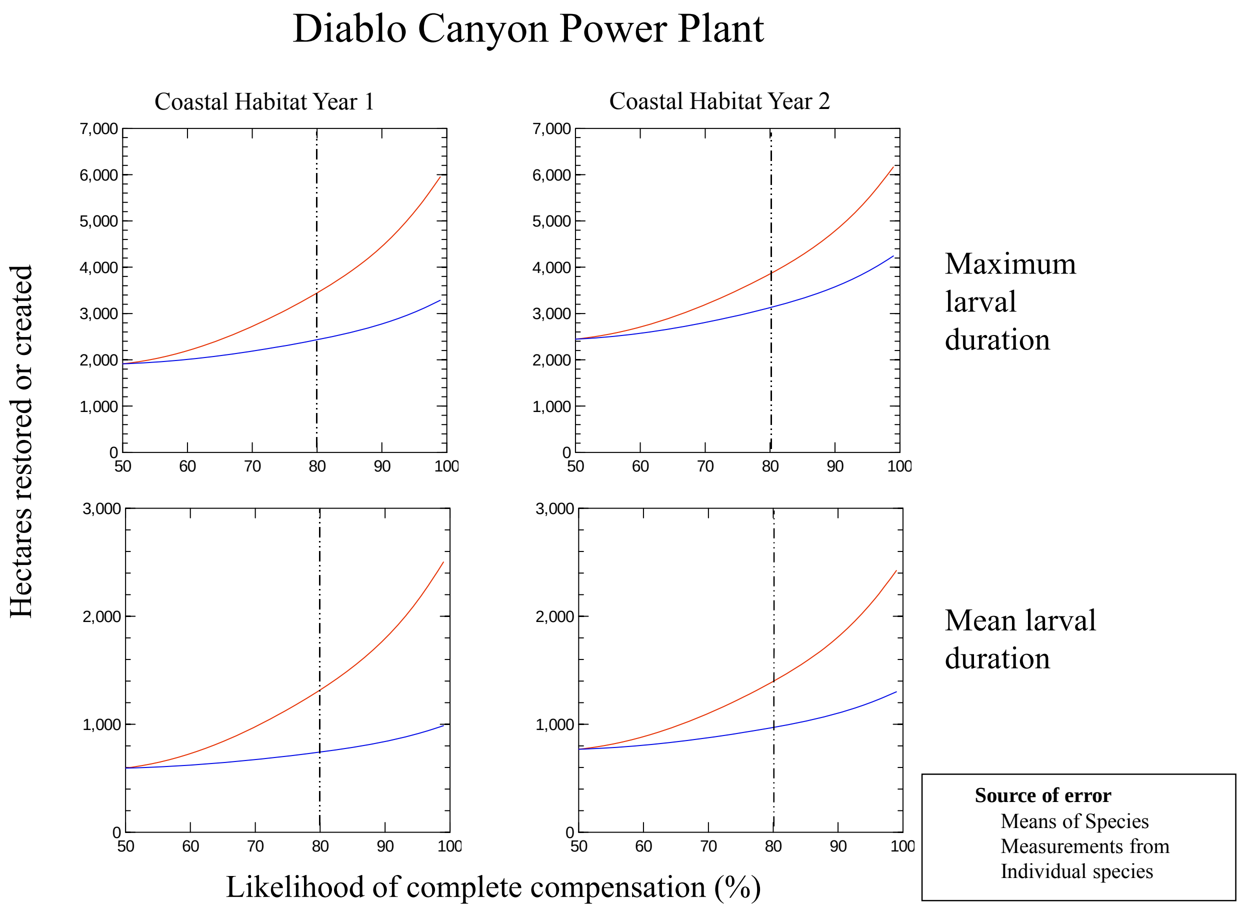

Figure 2d. Likelihood of complete compensation (%) Diablo Canyon Power Plant.

Morro Bay Power Plant

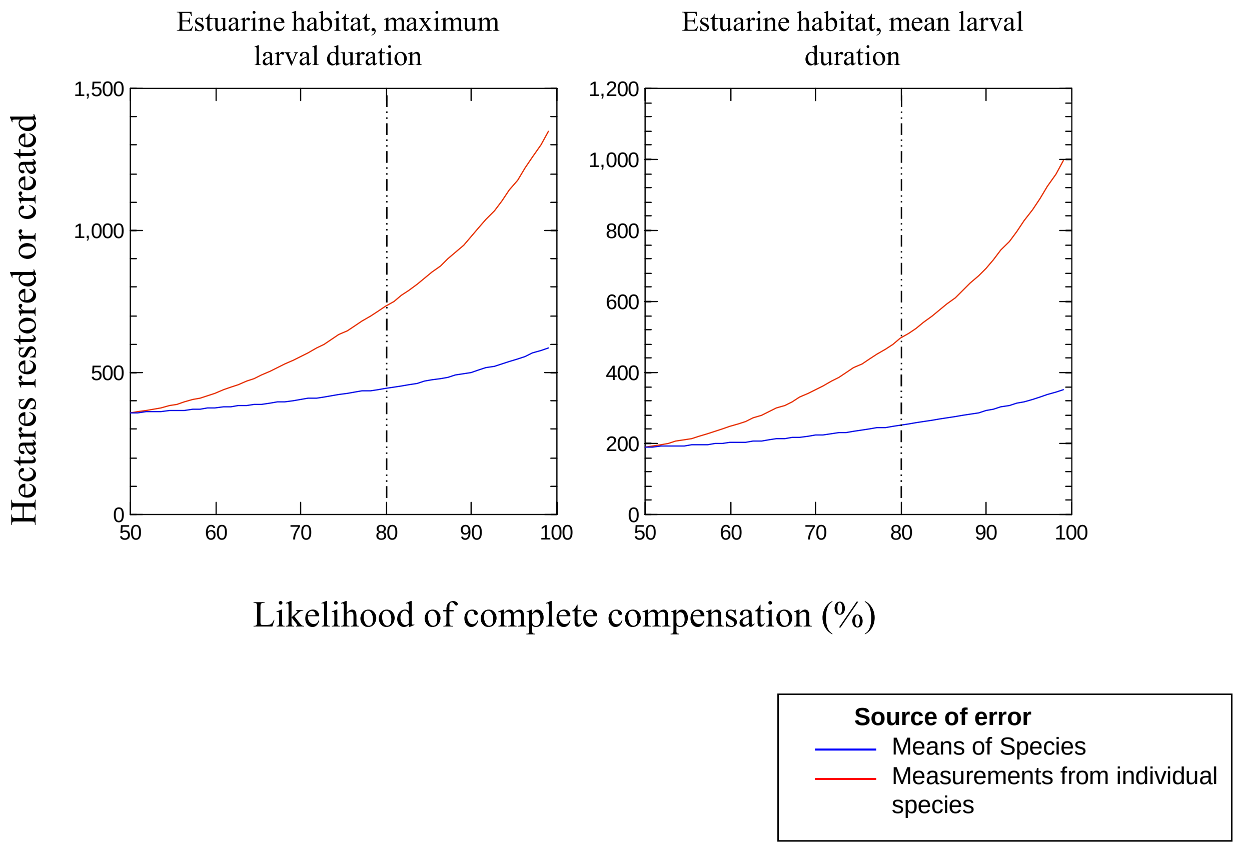

Figure 2e. Likelihood of complete compensation (%) Morro Bay Power Plant.

Moss Landing Power Plant

All results based on *mean* larval duration

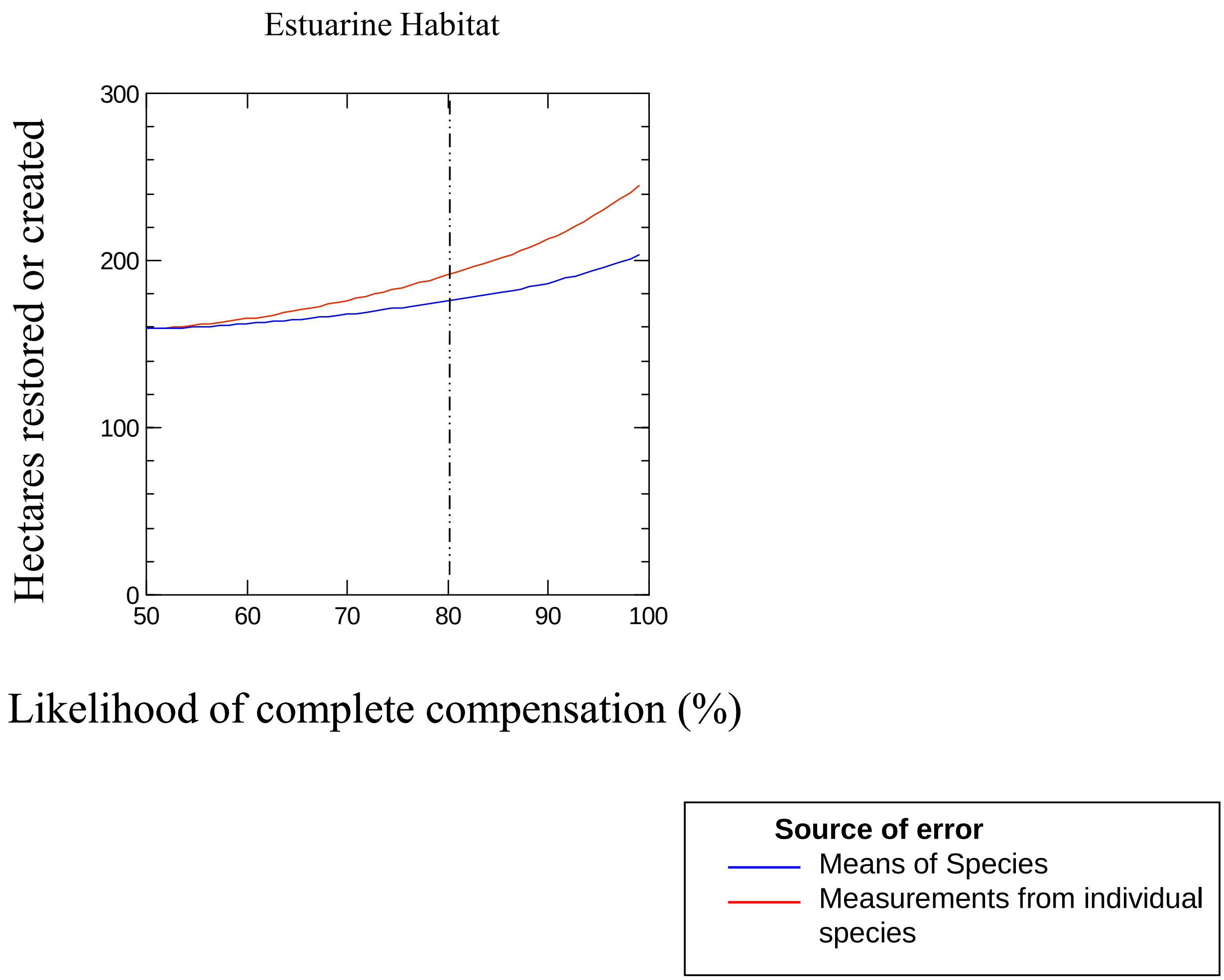

Figure 2f. Likelihood of complete compensation (%) Moss Landing Power Plant.

Potrero Power Plant

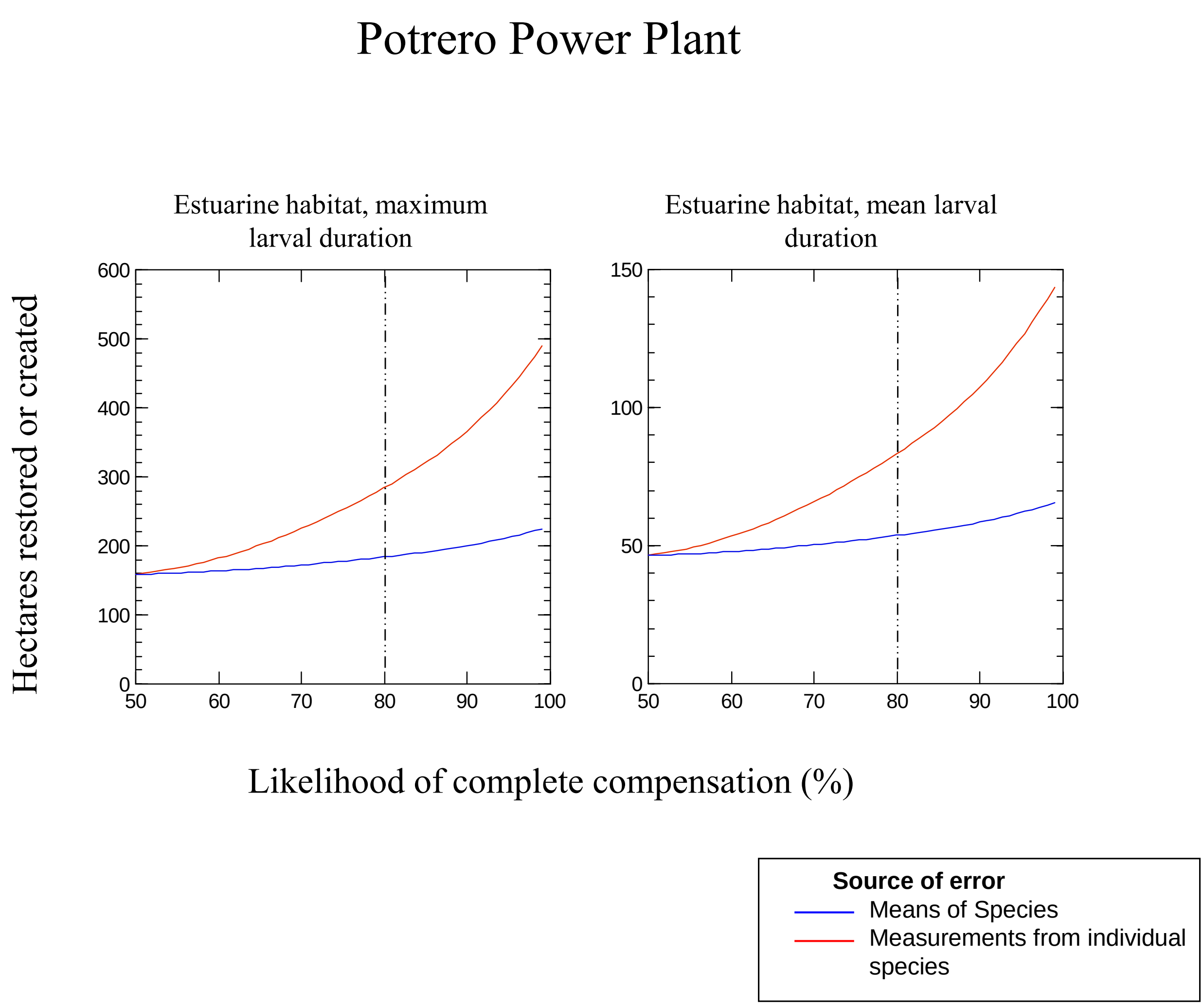

Figure 2g. Likelihood of complete compensation (%) Potrero Power Plant.